

# Catalysis and Surface Chemistry

## Research in the Mullins Lab



(updated July 7, 2014)



**Prof. Buddie Mullins**  
Chemical Engineering  
& Chemistry  
University of Texas at Austin

[mullins@che.utexas.edu](mailto:mullins@che.utexas.edu)

<http://research.engr.utexas.edu/mullins/>

*Our Research is Supported by the DOE  
and the Welch Foundation.*



### Participating Students

*We hope that this electronic flyer is useful to those interested in learning about the activities of our catalysis sub-group! Too little information? Don't hesitate to ask for further details!*

**Edward  
Evans**  
PhD Student



**Greg  
Mullen**  
PhD Student



**Jake Lam**  
Undergraduate  
Researcher



**Adrian  
Brush**  
PhD Student

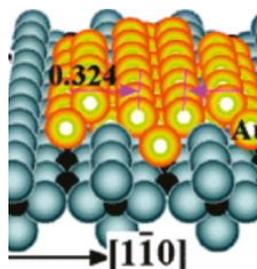


**Wen-Yueh  
Yu**  
PhD Student

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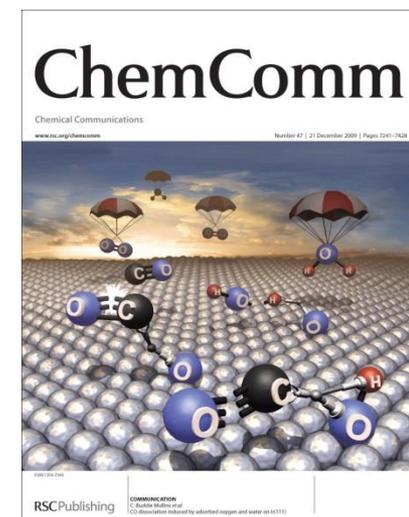
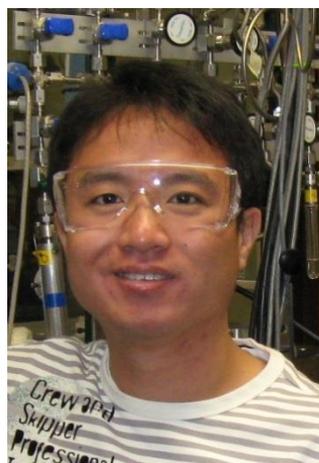
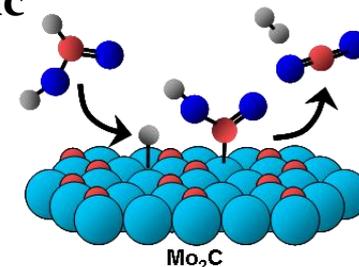
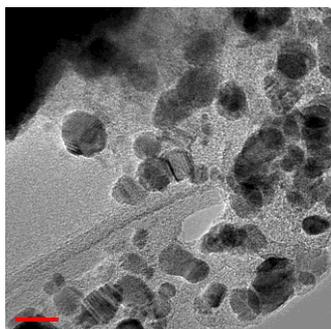
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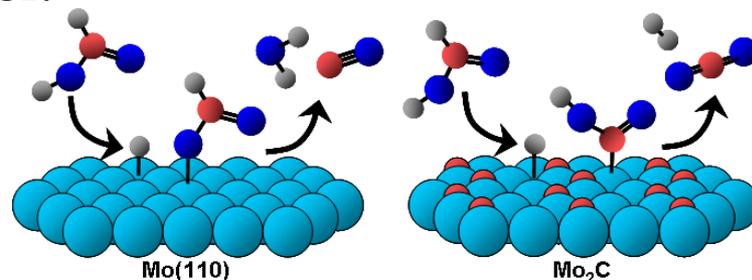
Mullins Research Group Photo



# Catalysis and Surface Chemistry

- Research Goals

- To better understand and unravel catalytic chemical mechanisms at the molecular level.



- The synthesis and characterization of high surface area catalysts for important chemical transformations.

- The training of graduate students for productive research careers in the chemical industry, national laboratories, or academia.

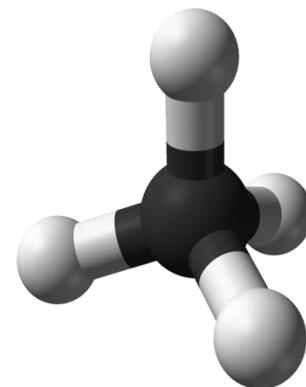


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# Research Activities

## Current Research Interests Include:

- Catalysis of Methane/Natural Gas:** For its conversion into useful liquid fuels or chemicals. **Natural gas** is very abundant on our planet but **methane** is a fairly inert molecule and it is quite difficult to convert into other useful species (especially those that are liquids at room temperature and pressure).



- Surface Chemistry/Catalysis of Gold:** The catalytic chemistry of supported nanoparticulate gold versus bulk gold. Au-Pd alloys and their catalytic chemistry. Oxidation and hydrogenation reactions. Although gold in macroscopic form is typically chemically inert (hence its use in dentistry and jewelry), in nanoparticle form gold can *selectively* catalyze reactions at low temperatures.

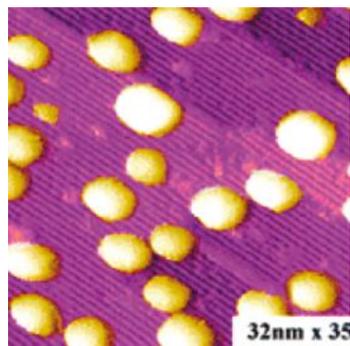


Image of Au nanoparticles on titania from Prof. W. Goodman.

- Transition Metal Carbide Catalysis/Surface Chemistry:** Promising catalytic properties from cheap materials. Mixed metal carbides and their properties for conversion of natural gas as well as for the water-gas shift reaction [ $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ ]. Transition metal carbides are of interest since they can possess catalytic behavior like platinum.

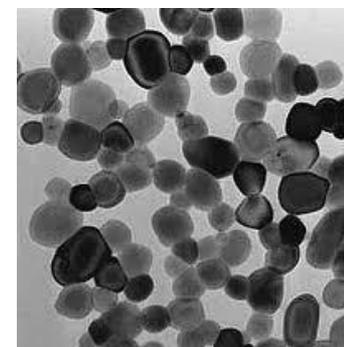
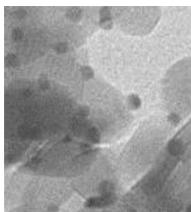
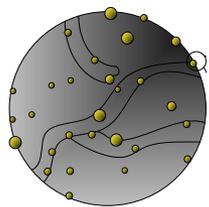


Image of TiC nanoparticles from: [www.nano-powders.net](http://www.nano-powders.net)

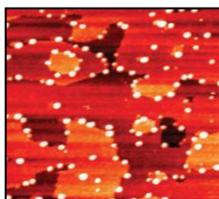
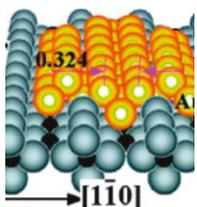
# Catalysis is Complex

Industrial catalysts are complex, porous materials that are used under very harsh conditions and this makes experimental study of the relevant chemistry extremely challenging. Use of model catalysts (e.g., pure, single-crystalline materials or planar wafers decorated with catalytically active nanoparticles) allows some of the features of industrial catalysts to be emulated. Additionally, less harsh conditions (lower pressures and temperatures) can be employed to allow use of spectroscopic tools that probe molecular level interactions (but this frequently changes the chemistry). Measurements of all types are useful for better understanding of catalysis.

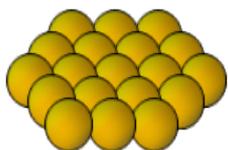
## Catalyst Complexity



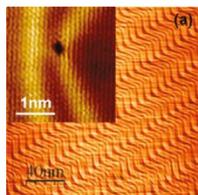
Porous, High-Surface Area Supported Particles



Planar Single-Crystal with Supported Particles

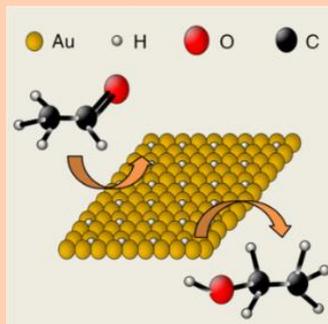


Single-Crystal Metal



## Model Systems

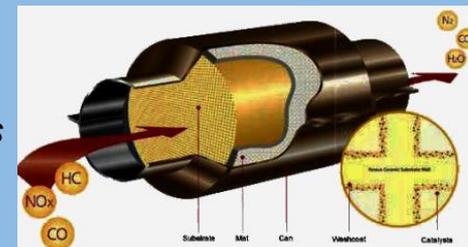
- *Uniform structure*



- *Clean background*
- *High sensitivity*

## Practical Systems

- *Metals*
- *Supports*
- *Interface*



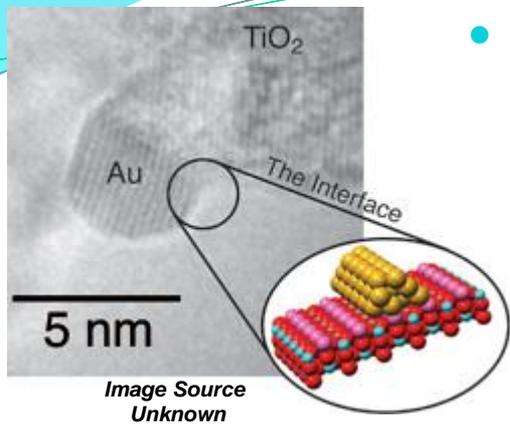
- *Particle shapes*
- *Particle sizes*

P ~ 10<sup>-10</sup> Torr  
T ~ 77 K

Reaction Conditions

High Pressure  
High Temperature

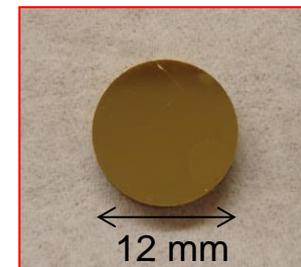
# Our Research Strategy



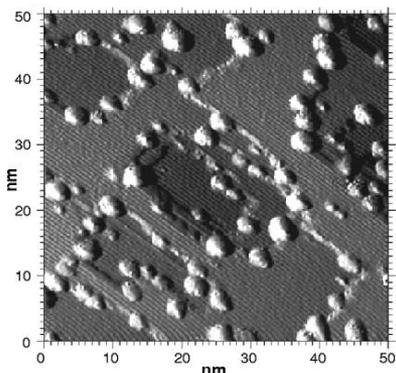
- **Synthesis and Characterization of High Surface Area Catalysts:** We are interested in synthesizing new catalysts for important catalytic reactions. We also characterize the catalyst by employing [scanning electron microscopy](#), [x-ray diffraction](#), [transmission electron microscopy](#) (see image to left), [Raman spectroscopy](#), [thermal gravimetric analysis](#), [surface area measurements](#), and, of course, reactivity performance measurements at atmospheric pressure and high temperature. The cartoon to the left suggests that the region between the nanoparticle and the support is an important interface for catalytic reactions.

- **Ultra-High Vacuum Surface Chemistry Studies of Model Catalysts:**

Here we study model catalysts in [ultra-high vacuum](#) ( $10^{-10}$  Torr) to minimize surface contamination. This also allows the use of electron-driven spectroscopies such as [low energy electron diffraction](#) and [Auger electron spectroscopy](#) as well as [Fourier transform infrared spectroscopy](#) for studying surface vibrations to determine the structure of the adsorbed species. [Mass spectrometry](#) is used for [temperature programmed desorption](#) and reactive molecular beam scattering measurements. This kind of data allows surface chemical details to be uncovered.



Highly polished single-crystal sample of gold exposing the [\(111\) face](#), i.e., Au(111).



Gold Clusters on Titania Wafer  
W. Goodman-Science (1998)

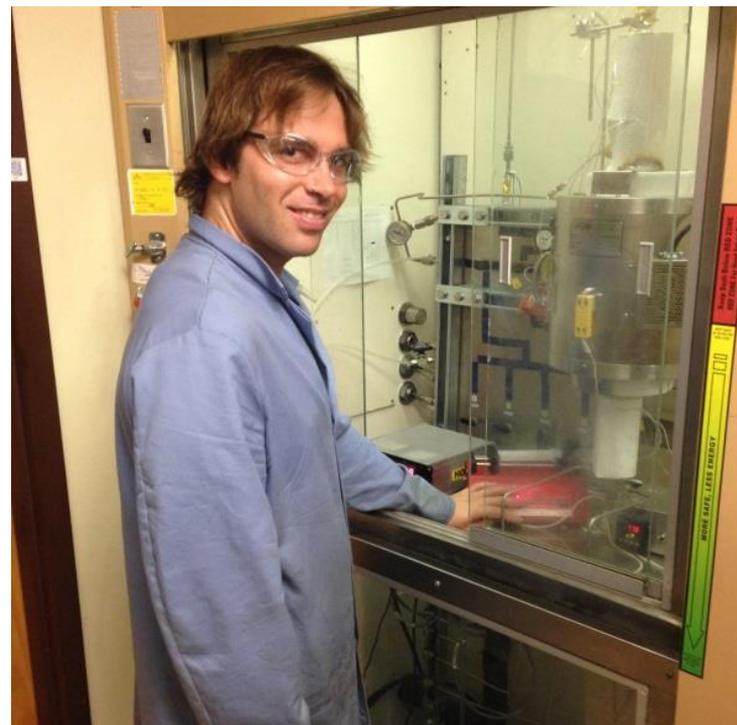
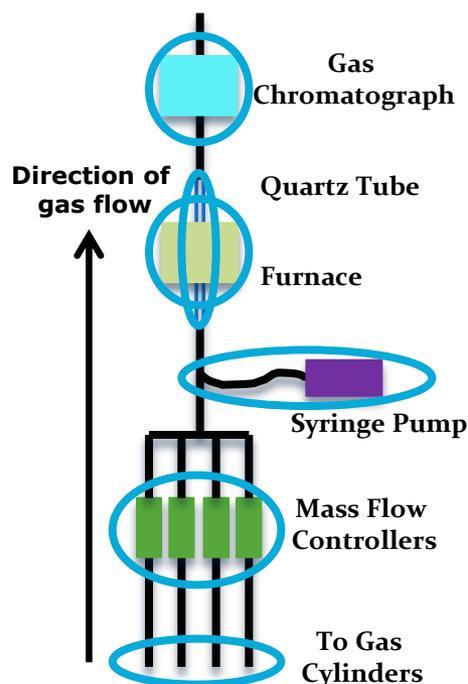
- **Reactivity Measurements at ~Atmospheric Pressure on Model Catalysts:** A [scanning tunneling microscopy](#) image of an example model catalyst is shown to the left (meant to chemically emulate the porous catalyst shown in the upper left of this slide). This kind of sample can be probed by electron-based spectroscopies in a vacuum chamber and yet also be tested for reactivity at pressures near atmospheric in a batch reactor at high temperature. This data is highly useful for bridging the gap between classical catalysis and vacuum measurements - an important area where much work is still to be done.

# High-Surface Area Classical Catalysis

- **Reaction Testing Apparatus:** Our system (shown at bottom left and in schematic) is comprised of a fixed-bed flow reactor capable of delivering four reactant gases and one volatile liquid across a catalyst bed held in a temperature controlled furnace. The effluent stream can be analyzed via a gas chromatograph to observe and quantify product generation.
- **Testing Activity of High-Surface Area Catalysts:** A major component of our work involves the study of novel catalysts for a host of important reactions. We are currently investigating gold catalysts for the water-gas shift reaction, mixed metal carbides for methane transformation, and transition metals supported on metal carbides for a host of hydrogenation and oxidation reactions.



*Reaction Testing Apparatus*

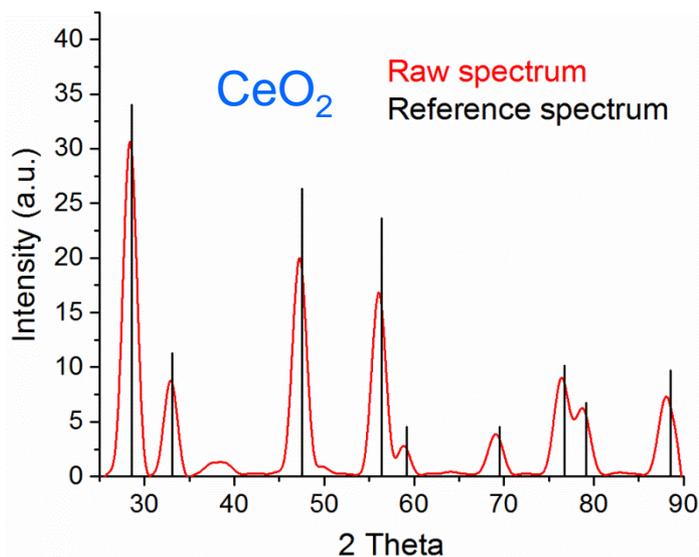


Adrian Brush working on the reactor (2014).

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# High-Surface Area Classical Catalysis

**Catalyst Synthesis:** We use a number of different techniques to create catalyst materials including [hydrothermal](#) and [sol-gel syntheses](#), temperature programmed carburization, deposition-precipitation, and cation exchange. These processes are used to synthesize both support materials and active catalysts. We have many useful tools in the lab for carrying out these techniques (tube furnaces, box furnaces, equipment for wet synthesis, etc.).



Greg Mullen synthesizing  $\text{V}_2\text{O}_5$  nanowires (2014).

The image to the right shows a high surface area  $\text{CeO}_2$  support material that was synthesized by precipitation of cerium nitrate in a basic solution. The [X-Ray diffraction](#) spectrum above displays characteristic  $\text{CeO}_2$  peaks, confirming a successful synthesis. Gold supported on  $\text{CeO}_2$  makes an excellent catalyst for the [water gas shift reaction](#).



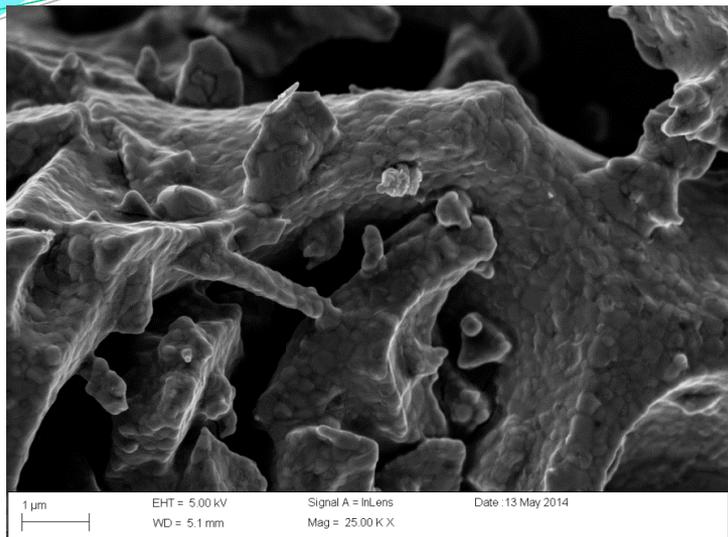
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The white powder on the left is  $\text{SiO}_2$  nanopowder after cation exchange with a gold precursor. After reduction in the tube furnace (middle image) the powder turns purplish, indicating the presence of gold nanoparticles. We use this as a reference catalyst for several reactions.

# High-Surface Area Classical Catalysis

## Analytical and Characterization Techniques

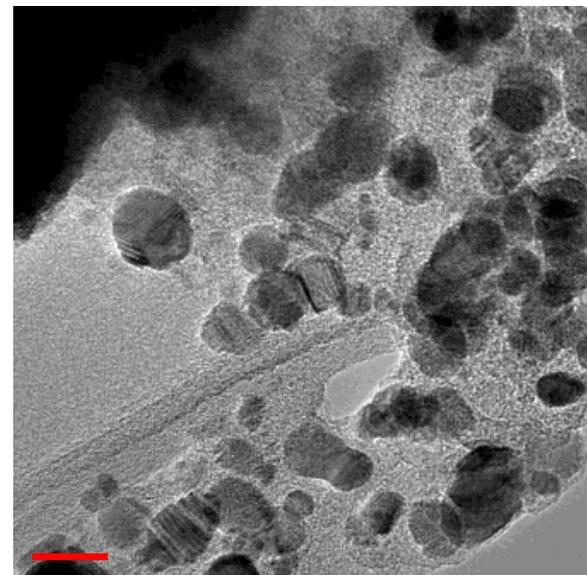


Scanning electron microscopy (SEM) image of doped molybdenum carbide catalyst.

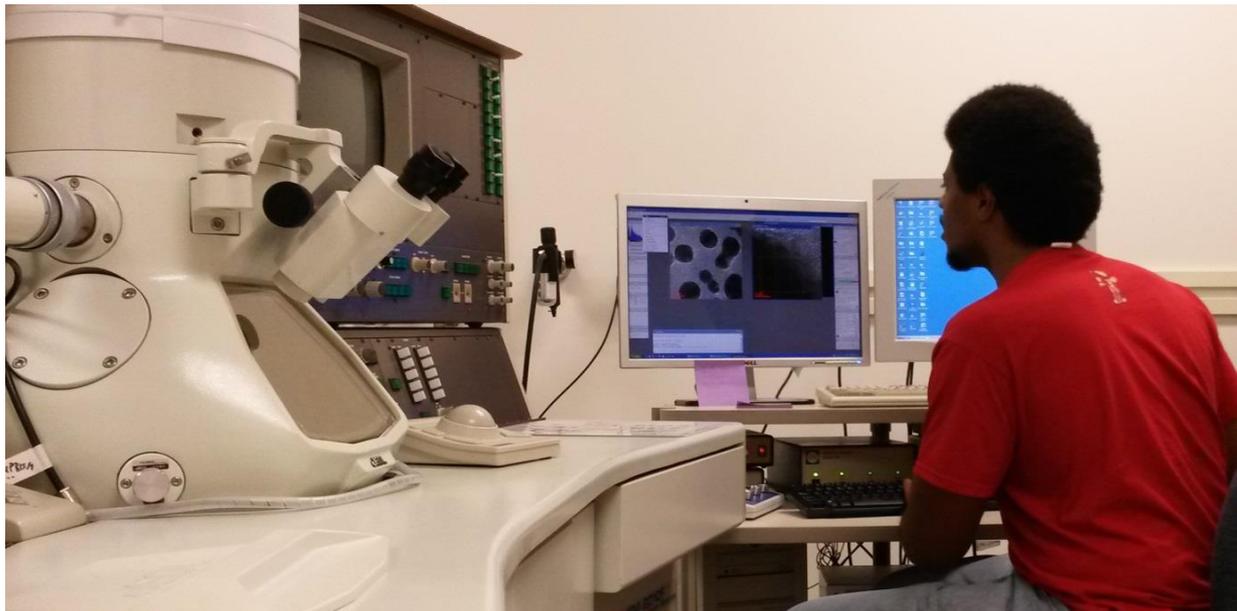
**Scanning** (SEM) and **transmission electron microscopy** (TEM) allow us to examine the catalyst morphology at the micron, nanometer, and even atomic scales. These two images indicate that the active part of the catalyst (the dark spots in the TEM image below right) are likely shown as the “bumps” seen in the SEM image to the left. These techniques can give spatially resolved composition information as well.



Adrian Brush loading the reactor (2014).



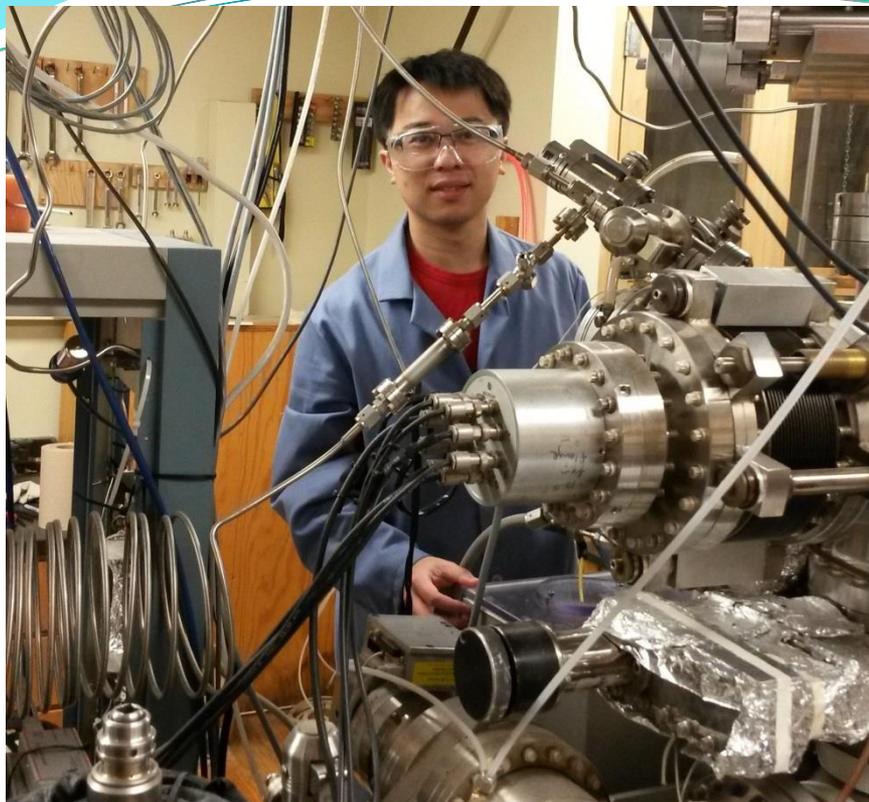
Transmission electron microscopy (TEM) image of doped molybdenum carbide catalyst.



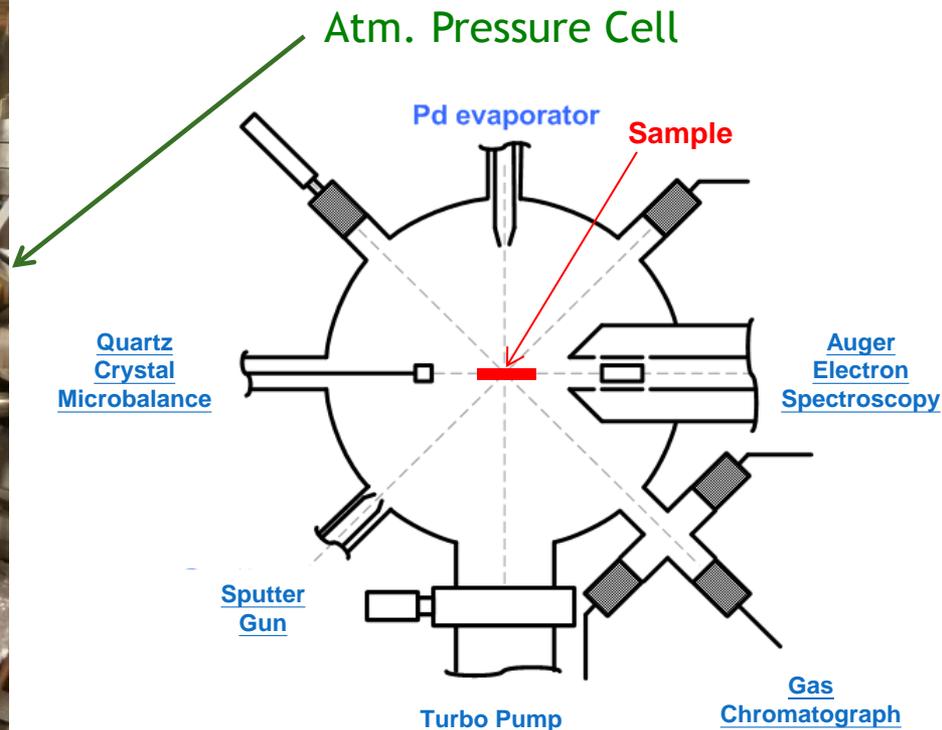
Edward Evans working on electron microscopy (2014).

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# Model Catalyst Studies at ~Atm. Pressure



Wen-Yueh Yu making measurements (2014).



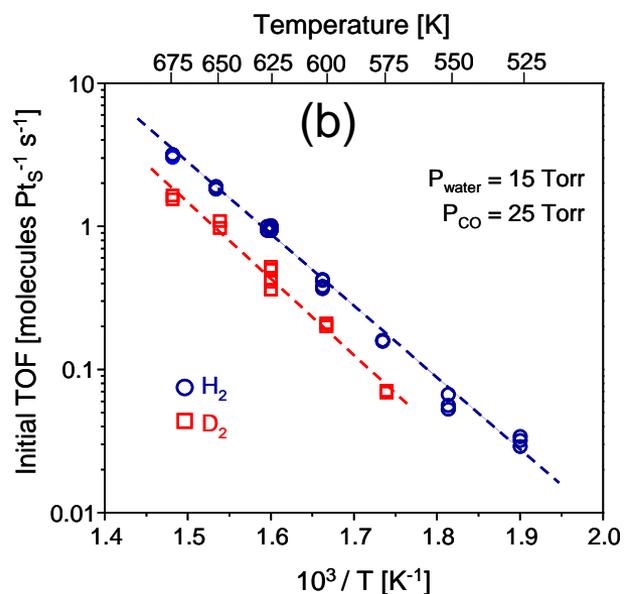
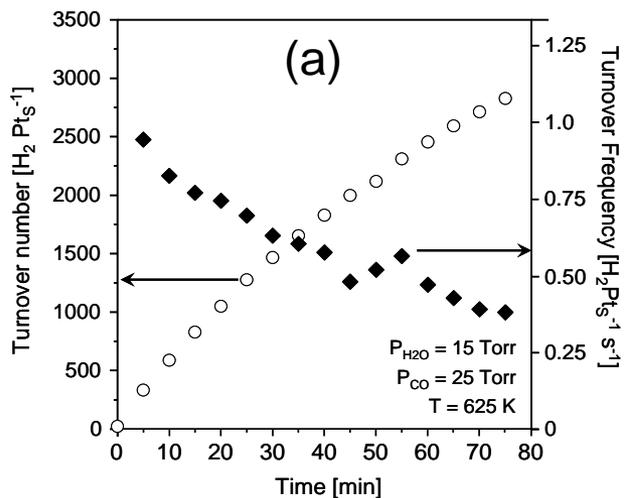
In these studies we employ a model planar catalyst that can be well characterized under ultra-high vacuum conditions and then use the sample to catalyze a reaction under pseudo-steady-state conditions at pressures close to atmospheric. We use a [gas chromatograph](#) to measure the time evolution of reaction products. We have studied single crystalline metals in this manner previously as well as single crystalline metal discs that are supporting metal-oxide nanoparticles. Measurements of this type are intermediate between the very clean studies we can perform under ultra-high vacuum conditions and the harsher high-surface-area studies we conduct in our flow reactor at atmospheric pressure (with less mechanistic insight).

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# Model Catalyst Studies at ~Atm. Pressure

## Example Measurements of the Water Gas Shift Reaction over Pt(111)

Here and on the next slide is a brief description of the type of measurements made in a typical study with model catalyst samples at pressures just below atmospheric pressure. A Pt(111) sample was used and the water-gas shift reaction (WGSR, i.e.,  $\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$ ), a reaction for producing hydrogen, was studied in this case.



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Greg Mullen adjusting the Gas Chromatograph (2014).

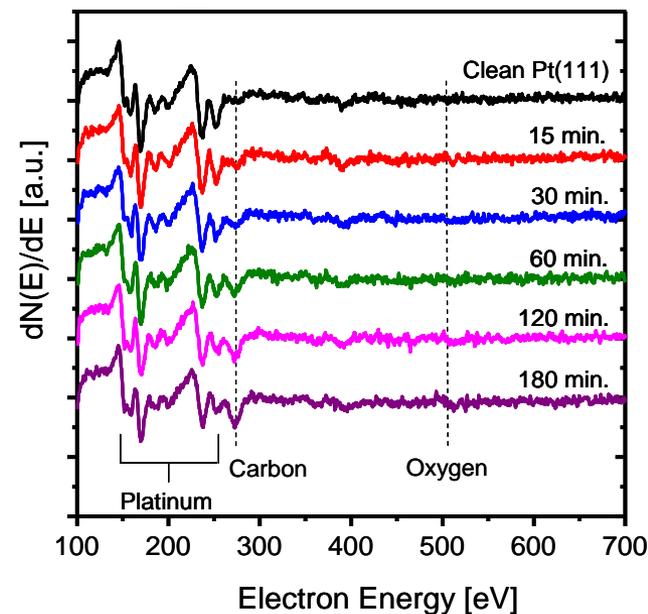
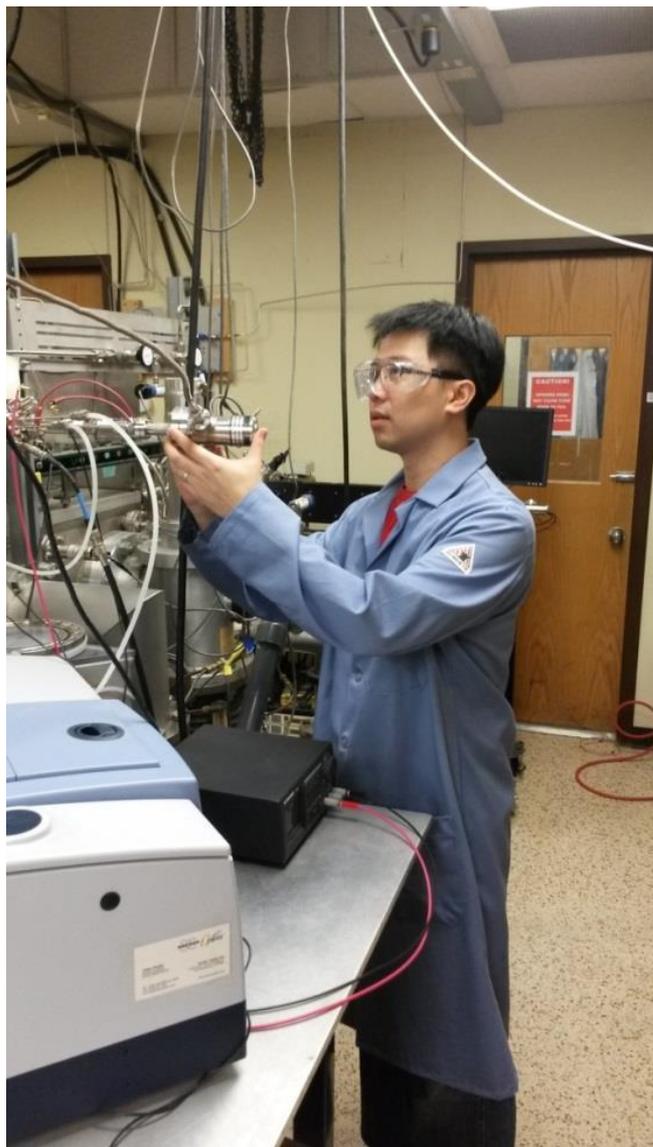
The upper left panel (a) shows the formation rate of  $\text{H}_2$  due to the water-gas shift reaction with respect to time, per Pt site. Data such as these are acquired by bleeding a small amount of gas from the reaction chamber into the [gas chromatograph](#) and analyzing and quantifying it. In panel (b) we show an Arrhenius plot of the formation rates of hydrogen (and [deuterium](#)  $\text{D}_2$  - from  $\text{D}_2\text{O}$ ) constructed from measurements such as those on the left conducted at many different temperatures. Here the data indicate a [kinetic isotope effect](#) is in effect, as might be expected if water dissociation were an important step in the reaction mechanism.

# Model Catalyst Studies at ~Atm. Pressure

## Example Measurements of the Water Gas Shift Reaction over Pt(111) - II

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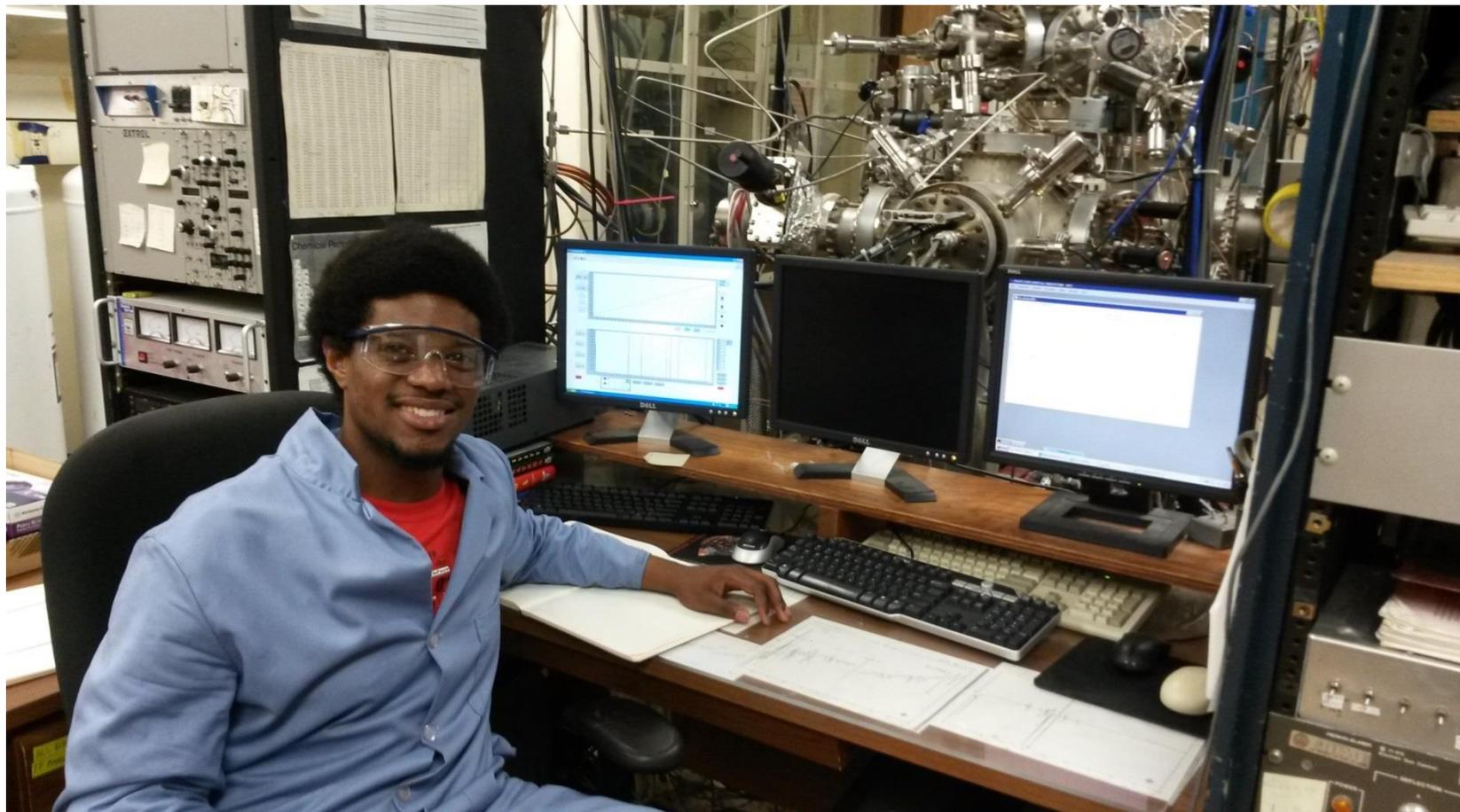
Wen-Yueh Yu  
taking data  
(2014).



Auger electron spectra of the Pt(111) surface following the WGSR (with partial pressures  $P_{CO} = 25$  Torr and  $P_{H_2O} = 15$  Torr at 575 K). After the indicated times, the sample was held at 550 K while the chamber was quickly evacuated, followed by acquiring the Auger spectra at 550 K to prevent the accumulation of residual CO during analysis. Carbon accumulates on the surface (the feature at 273 eV) as the reaction proceeds, reducing the catalytic activity of the surface.

# Ultra-High Vacuum Apparatus for Studying Model Catalysts

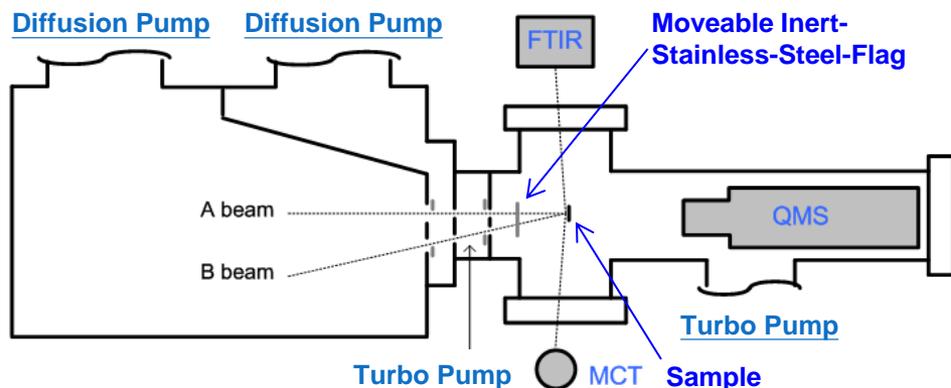
We study model catalyst samples (e.g., single-crystalline metals or metal oxide wafers decorated with metal nanoparticles) in an **ultra-high vacuum** environment ( $10^{-10}$  Torr) in order to keep the sample surface free of contaminating molecules and to allow the use of various electron-driven spectroscopies (shown in the next few pages). We frequently employ cryogenic sample temperatures (i.e., **liquid nitrogen** cooling of the sample) to slow down chemical reactions and to stabilize surface intermediate species for spectroscopic probing.



**Edward Evans taking data on one of our ultrahigh vacuum (UHV) surface chemistry instruments (2014).**

# Ultra-High Vacuum Apparatus for Studying Model Catalysts

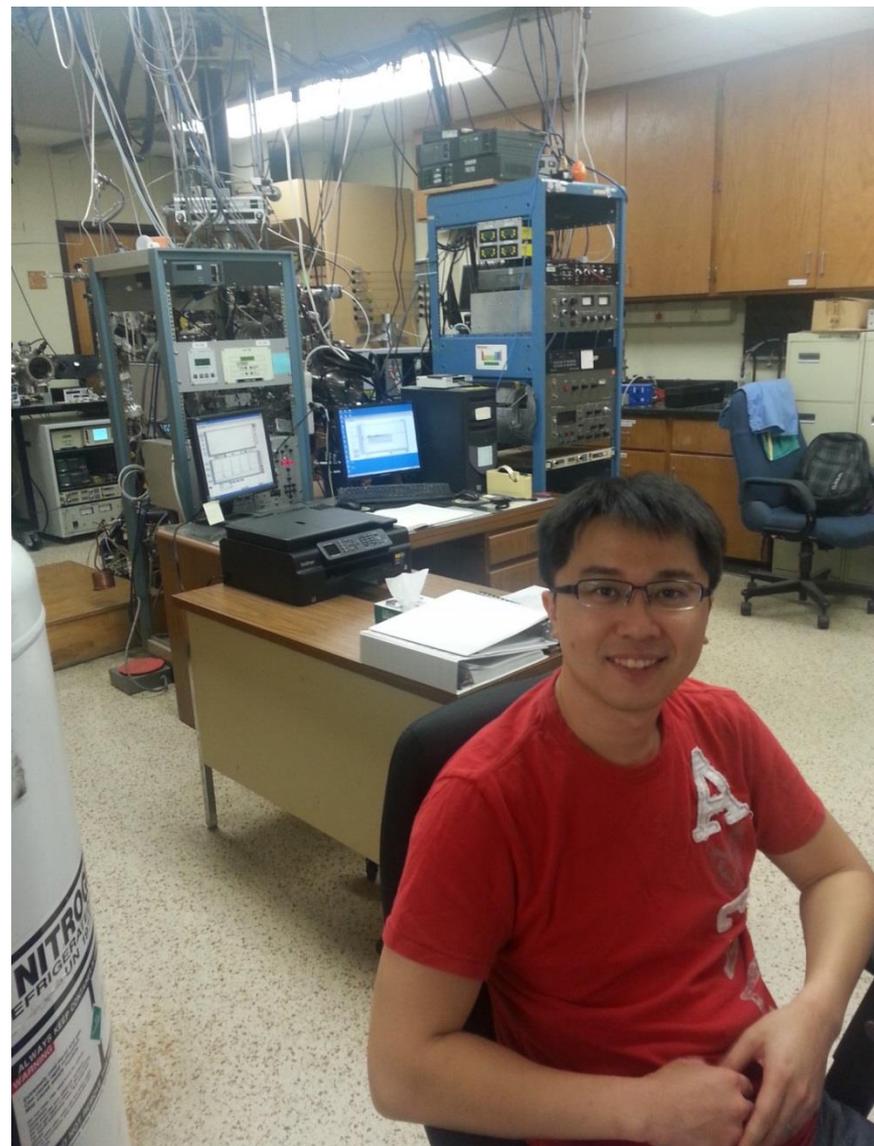
## Reactive Molecular Beam Scattering Provides Insights into Surface Interactions



More details on this particular apparatus can be found in:  
*J. Phys. Chem. C* **113**, 12742-12752 (2009). <http://dx.doi.org/10.1021/jp904236v>

In the apparatus schematic shown above it can be seen that two collimated molecular beams can be formed that impinge on a model catalyst sample. A moveable stainless-steel-flag can block both beams from striking the sample under study (as explained for the data on the next slide). The pressure in the chamber is  $\sim 10^{-10}$  Torr in order to greatly reduce/eliminate contaminating the surface under study. A **mass spectrometer** (QMS) is used to measure gas-phase molecules that evolve from the surface either from molecular beam scattering measurements (described below) or **temperature programmed desorption** measurements (described in a few slides). Surface vibrational spectroscopy measurements can be made employing a **Fourier Transform InfraRed** (FTIR) source and detector (MCT) (described in two slides). The chamber is also typically equipped with a few evaporators so that nanoparticles can be added to the surface *in situ*.

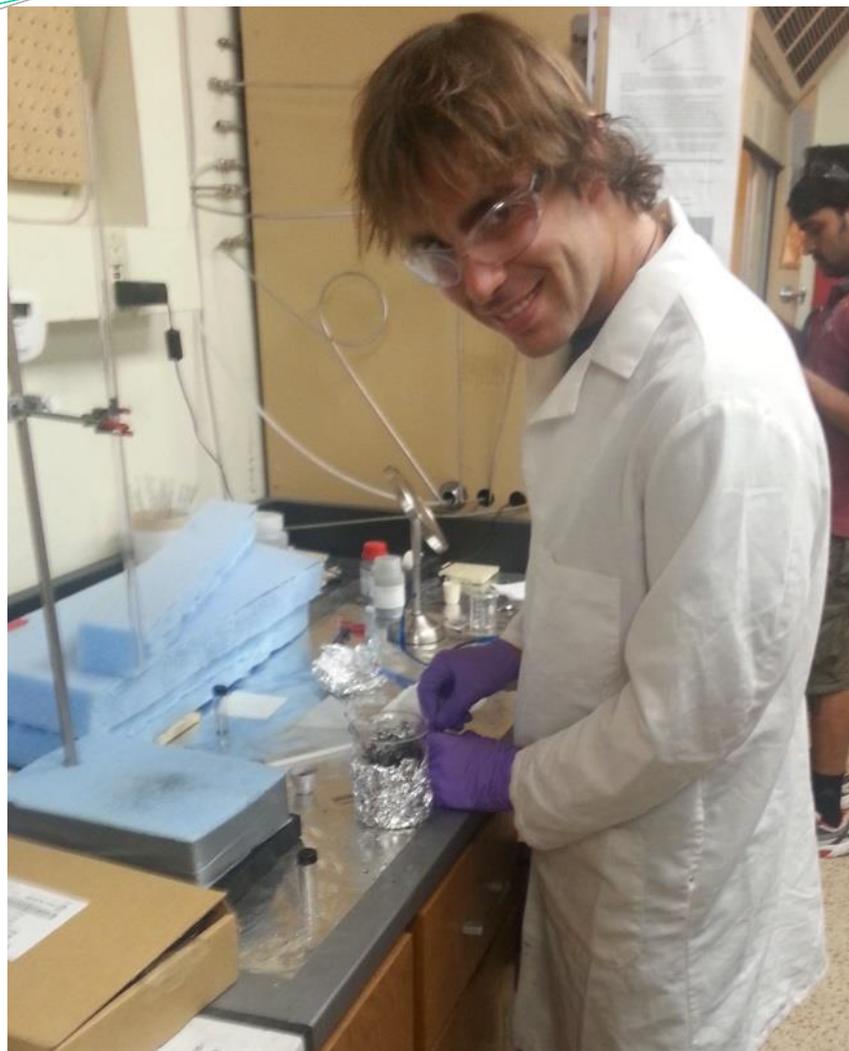
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Wen-Yueh Yu with his UHV apparatus (2014).

# Ultra-High Vacuum Apparatus for Studying Model Catalysts

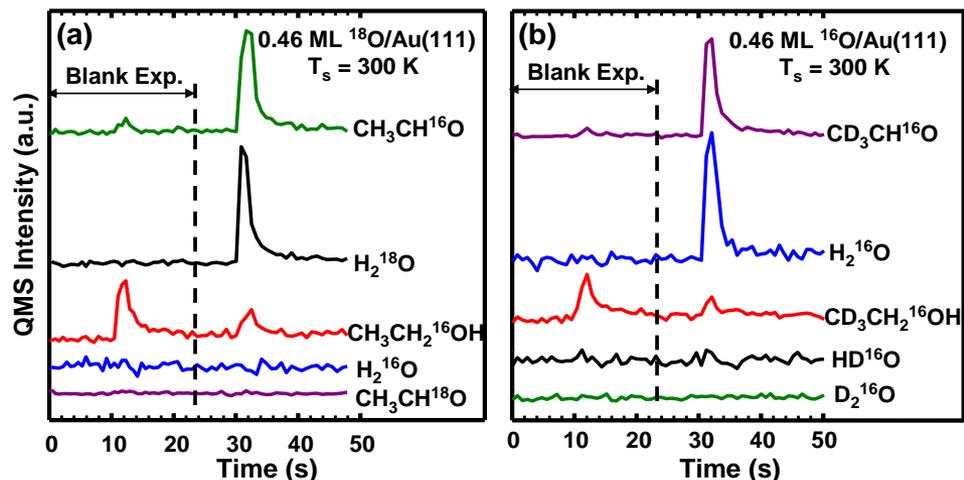
## Reactive Molecular Beam Scattering Provides Insights into Surface Interactions



With a sly look on his face Adrian Brush works on a Ni-Mo<sub>2</sub>C catalyst (2014).

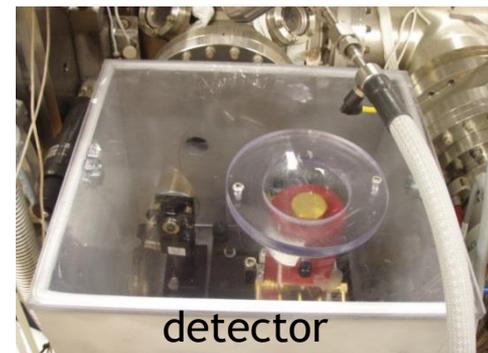
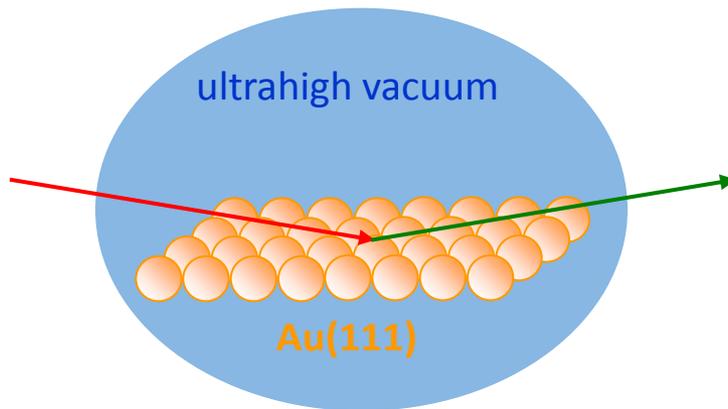
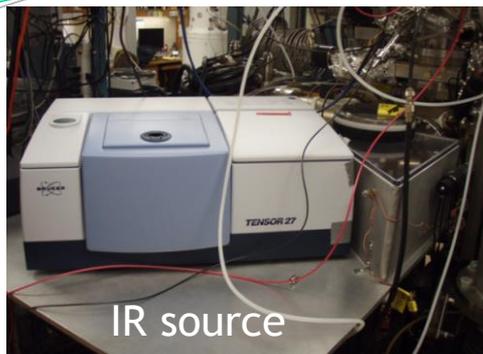
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Below, data from a molecular beam of ethanol striking a gold surface precovered with atomic oxygen for study of the oxidation of ethanol to acetaldehyde. The [quadrupole mass spectrometer](#) (QMS) was used to measure the evolution of acetaldehyde and water from (a) C<sub>2</sub>H<sub>5</sub>OH impingement on <sup>18</sup>O<sub>a</sub> (isotopically labelled oxygen) pre-covered Au(111) at 300 K (from  $t = 30$  s to 32 s); and (b) partially-deuterated ethanol (CD<sub>3</sub>CH<sub>2</sub>OH) impingement on <sup>16</sup>O<sub>a</sub> pre-covered Au(111) at 300 K ( $t = 30$  s to 32 s). A “blank experiment” is shown from  $t \approx 10$ -12 s in which the ethanol beam is impinged on an inert-stainless-steel flag placed in front of the Au(111) surface (so that no reaction can take place). From 30s to 32s the ethanol beam strikes the gold sample and it is seen that the signal for water and acetaldehyde increase indicating oxidation of the ethanol. Also note that the signal for the ethanol decreases from 30-32s compared to 10-12s since some of it is being reacted into the aldehyde. The small signal for the aldehyde seen from 10-12s is due to the ionizer in the QMS which causes partial dissociation of the ethanol (to a mass the same as the aldehyde).

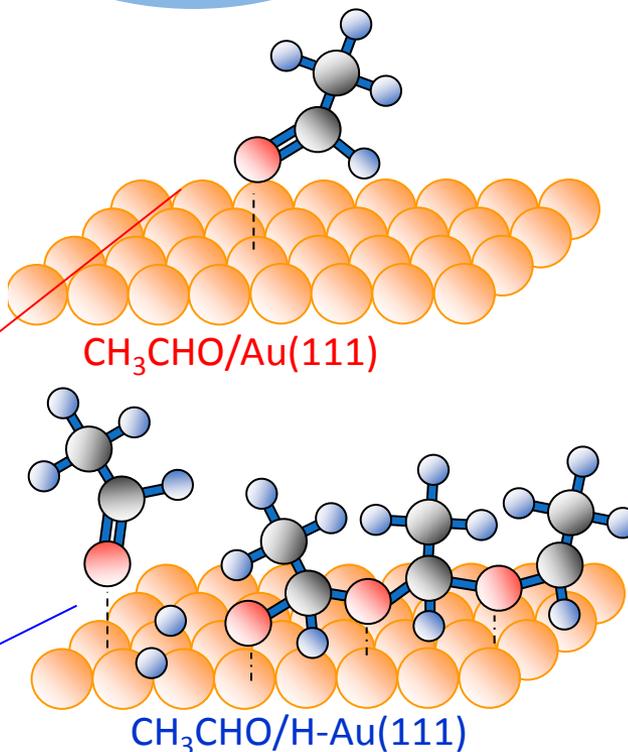
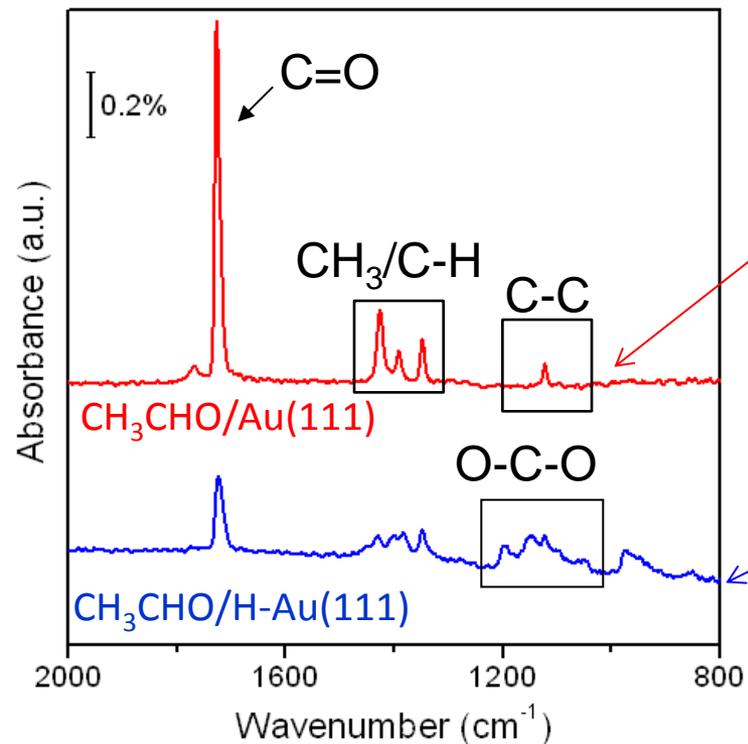


# Ultra-High Vacuum Apparatus for Studying Model Catalysts

## Surface Vibrational Spectroscopy (FTIR) Can Decipher the Structure of Adsorbed Species



In these measurements, infrared light of varying wavelength is reflected (at a very glancing angle) from the crystal surface. The atomic vibrations of molecules and molecular fragments on the surface absorb light at specific frequencies. The spectra can be analyzed to provide information about the structure of the species on the surface after reaction. In the data shown in the far left, the red curve is the characteristic spectra expected for an “intact” adsorbed acetaldehyde molecule while the blue curve shows the spectra for acetaldehyde reacting with hydrogen pre-adsorbed on the gold surface. The blue spectra suggests that the acetaldehyde has “polymerized” on the surface as shown in the cartoon.



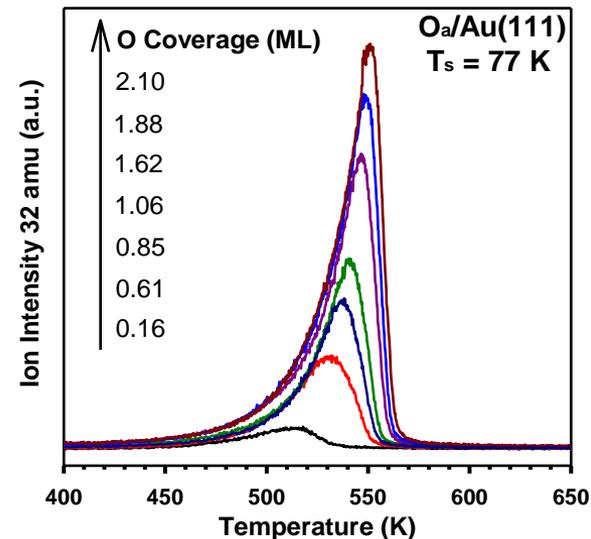
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# Ultra-High Vacuum Apparatus for Studying Model Catalysts

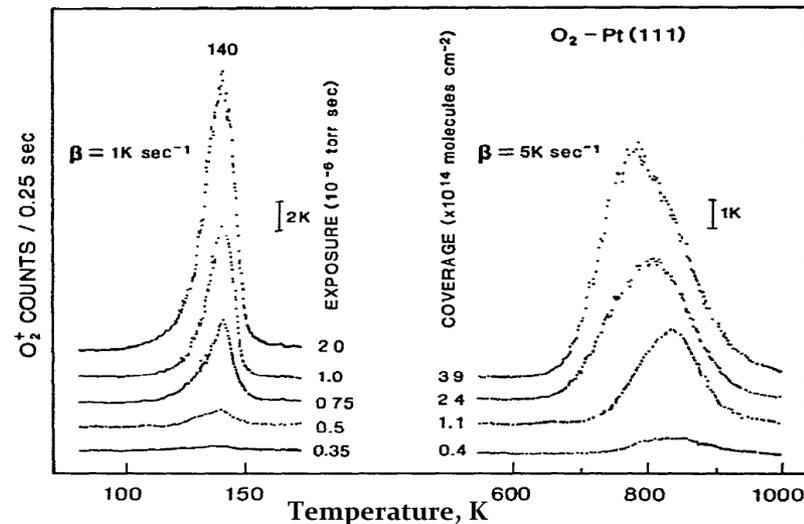
## Temperature Programmed Desorption Used to Study Surface Reactivity and Binding

In temperature programmed desorption (TPD) measurements, the sample is covered with molecules of interest and then heated (temperature increases with time linearly). The adsorbed molecules or atoms will desorb from the surface over a temperature range characteristic of their binding energy to the surface (and are measured by mass spectrometry). Typically this temperature range changes as the nature of the surface changes and also with different molecules. On the left, hydrogen (and deuterium) atoms are shown to recombine into molecules on the gold surface and desorb with a peak temperature of  $\sim 110$ - $120$  K. In the upper panel to the right oxygen is shown to desorb from Au(111) between 450-570 K. This indicates that oxygen binds to the gold surface more strongly than hydrogen.

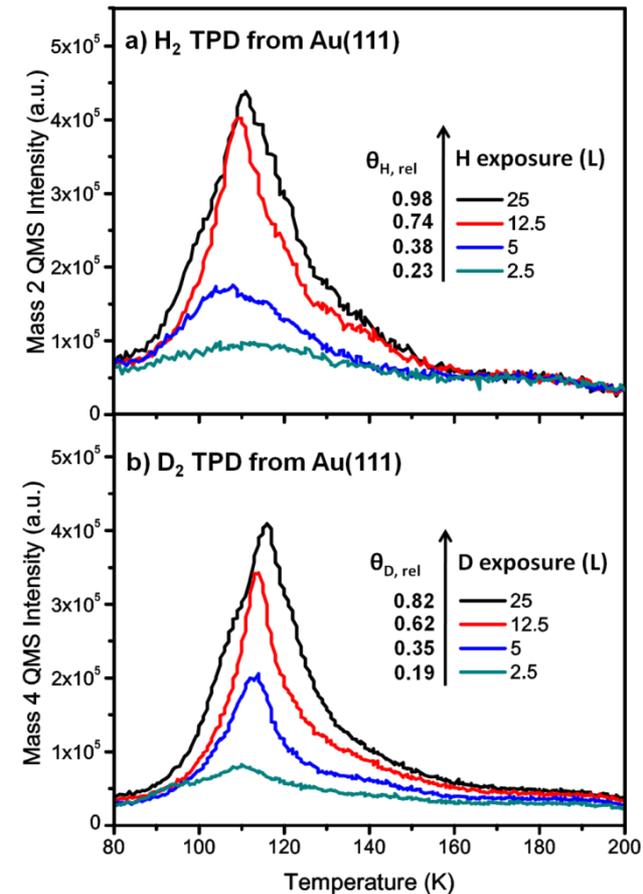
This is the case for many metals. In the lower right panel spectra for O<sub>2</sub> desorption from Pt(111) is shown. Two peaks appear since on this surface oxygen initially binds as an intact chemisorbed molecule, some of which desorbs at  $\sim 135$ K, with some of the molecules dissociating and then recombining and desorbing between 700-950K, showing that oxygen binds more strongly to Pt than Au.



O<sub>2</sub> TPD spectra from Au(111).  
*J. Phys. Chem. C* **112**, 5501-5509 (2008).  
<http://dx.doi.org/10.1021/jpo763735>



O<sub>2</sub> TPD spectra from Pt(111). *Chem. Phys. Lett.* **96**, 371-373 (1983).  
<http://www.sciencedirect.com/science/article/pii/0009261483806927>



H<sub>2</sub> (a) and D<sub>2</sub> (b) TPD spectra from Au(111). *J. Phys. Chem. Lett.* **2**, 1363-1367 (2011).  
<http://dx.doi.org/10.1021/jz200577n>

# COLLABORATORS



**Prof. Gyeong S. Hwang**

Prof. Hwang and his group perform density functional calculations to complement our experiments.

<http://www.che.utexas.edu/gshwang/>



**Prof. Graeme Henkelman**

Prof. Henkelman and his group perform density functional calculations to complement our experiments.

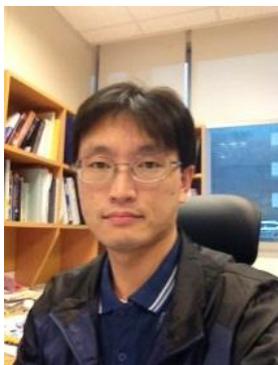
<http://theory.cm.utexas.edu/henkelman/>



**Prof. Dick Crooks**

Prof. Crooks and his group work with us in the study of electrocatalysts.

<http://rcrooks.cm.utexas.edu/research/>



**Dr. Hyung Chul Ham**

Formerly in the Hwang Group  
Now at Korean Institute of Science and Technology Seoul



**Liang Zhang**

Graduate Student in the Henkelman Group

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**Dr. Jose Rodriguez**

Dr. Rodriguez collaborates with us in surface chemistry measurements.

<http://www.chemistry.bnl.gov/sciandtech/crs/staff/jose.htm>

# CATALYSIS AND SURFACE CHEMISTRY PUBLICATIONS

## (From 2011 – June 2014)

- Wen-Yueh Yu, Gregory M. Mullen, David W. Flaherty, and C. Buddie Mullins, "Selective hydrogen production from formic acid decomposition on Pd-Au bimetallic surfaces," *J. Am. Chem. Soc.* submitted.
- Gregory M. Mullen, Liang Zhang, Edward J. Evans Jr., Ting Yan, Graeme Henkelman, and C. Buddie Mullins, "Oxygen and hydroxyl species induce multiple reaction pathways for the partial oxidation of allyl alcohol on gold," *J. Am. Chem. Soc.* **136**, 6489-6498 (2014). <http://dx.doi.org/10.1021/ja502347d>
- Stephen E. Fosdick, Sean P. Berglund, C. Buddie Mullins, and Richard M. Crooks, "Evaluating electrocatalysts for the hydrogen evolution reaction using bipolar electrode arrays: Bi- and trimetallic combinations of Co, Fe, Ni, Mo, and W," *ACS Catal.* **4**, 1332-1339 (2014). <http://dx.doi.org/10.1021/cs500168t>
- Wen-Yueh Yu, Gregory M. Mullen, C. Buddie Mullins, "Interactions of hydrogen and carbon monoxide on Pd-Au bimetallic surfaces," *J. Phys. Chem. C* **118**, 2129-2137 (2014). <http://dx.doi.org/10.1021/jp411299e>
- Ming Pan, Jinlong Gong, Guangbin Dong, and C. Buddie Mullins, "Model studies with gold: A versatile oxidation and hydrogenation catalyst," *Acc. Chem. Res.* **47**, 750-760 (2014). <http://dx.doi.org/10.1021/ar400172u>
- Wen-Yueh Yu, Gregory M. Mullen, C. Buddie Mullins, "Hydrogen adsorption and absorption with Pd-Au bimetallic surfaces," *J. Phys. Chem. C* **117**, 19535-19543 (2013). <http://dx.doi.org/10.1021/jp406736b>
- Gregory M. Mullen, Jinlong Gong, Ting Yan, Ming Pan, and C. Buddie Mullins, "The effects of adsorbed water on gold catalysis and surface chemistry," *Top. Catal.* **56**, 1499-1511 (2013). <http://dx.doi.org/10.1007/s11244-013-0143-x>
- Ming Pan, Adrian Brush, Zachary D. Pozun, Hyung Chul Ham, Wen-Yueh Yu, Graeme Henkelman, Gyeong S. Hwang, and C. Buddie Mullins, "Model studies of heterogeneous catalytic hydrogenation reactions with gold," *Chem. Soc. Rev.* **42**, 5002-5013(2013). <http://dx.doi.org/10.1039/c3cs35523c>
- Stephen E. Fosdick, Sean P. Berglund, C. Buddie Mullins, and Richard M. Crooks, "Parallel screening of electrocatalyst candidates using bipolar electrochemistry," *Anal. Chem.* **85**, 2493-2499 (2013). <http://dx.doi.org/10.1021/ac303581b>
- Ming Pan, Hyung Chul Ham, Wen-Yueh Yu, Gyeong S. Hwang, and C. Buddie Mullins, "Highly selective, facile NO<sub>2</sub> reduction to NO at cryogenic temperatures on H pre-covered gold," *J. Am. Chem. Soc.* **135**, 436-442 (2013). <http://dx.doi.org/10.1021/ja3096575>
- Adrian J. Brush, Ming Pan, and C. Buddie Mullins, "Methanol O-H bond dissociation on H-precovered gold originating from a structure with a wide range of surface stability," *J. Phys. Chem. C* **116**, 20982-20989 (2012). <http://dx.doi.org/10.1021/jp308099y>

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# CATALYSIS AND SURFACE CHEMISTRY PUBLICATIONS

## (From 2011 – June 2014 – Cont.)

- Ming Pan, Adrian J. Brush, Guangbin Dong, and C. Buddie Mullins, "Tunable ether production via coupling of aldehydes or aldehyde/alcohol over hydrogen-modified gold catalysts at low temperature," *J. Phys. Chem. Lett.* **3**, 2512-2516 (2012). <http://dx.doi.org/10.1021/jz301105e>
- Ting Yan, Daniel W. Redman, Wen-Yueh Yu, David W. Flaherty, Jose A. Rodriguez, and C. Buddie Mullins, "CO oxidation on inverse Fe<sub>2</sub>O<sub>3</sub>/Au(111) model catalysts," *J. Catal.* **294**, 216-222 (2012). <http://dx.doi.org/10.1016/j.jcat.2012.07.024>
- Ming Pan, Zachary D. Pozun, Wen-Yueh Yu, Graeme Henkelman, and C. Buddie Mullins, "Structure revealing H/D exchange with co-adsorbed hydrogen and water on gold," *J. Phys. Chem. Lett.* **3**, 1894-1899 (2012). <http://dx.doi.org/10.1021/jz3007707>
- Ming Pan, Zachary D. Pozun, Adrian J. Brush, Graeme Henkelman, and C. Buddie Mullins, "Low-temperature chemoselective gold-surface-mediated hydrogenation of acetone and propionaldehyde," *ChemCatChem* **4**, 1241-1244 (2012). <http://dx.doi.org/10.1002/cctc.201200311>
- David W. Flaherty, Wen-Yueh Yu, Zachary D. Pozun, Graeme Henkelman, and C. Buddie Mullins, "Mechanism for the water-gas shift reaction on monofunctional platinum and cause of catalyst deactivation," *J. Catal.* **282**, 278-288 (2011). <http://dx.doi.org/10.1016/j.jcat.2011.06.024>
- Ming Pan, David W. Flaherty, and C. Buddie Mullins, "Low-Temperature Hydrogenation of Acetaldehyde to Ethanol on H pre-covered Au(111)," *J. Phys. Chem. Lett.* **2**, 1363-1367 (2011). <http://dx.doi.org/10.1021/jz200577n>
- Ting Yan, Jinlong Gong, David W. Flaherty, and C. Buddie Mullins, "The effect of adsorbed water in CO oxidation on Au/TiO<sub>2</sub>(110)," *J. Phys. Chem. C* **115**, 2057-2065 (2011). <http://dx.doi.org/10.1021/jp109295u>
- Ming Pan, Son Hoang, and C. Buddie Mullins, "Interaction of water with the clean and oxygen precovered Ir(111) surface," *Catal. Today* **160**, 198-203 (2011). <http://dx.doi.org/10.1016/j.cattod.2010.05.008>

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# Catalysis and Surface Chemistry Lab Recent Alumni

## Recently Graduated Ph.D. Students



**Ting Yan**  
Ph.D. May 2013  
Intel Corp.



**Ming Pan**  
Ph.D. May 2013  
National Renewable  
Energy Laboratory

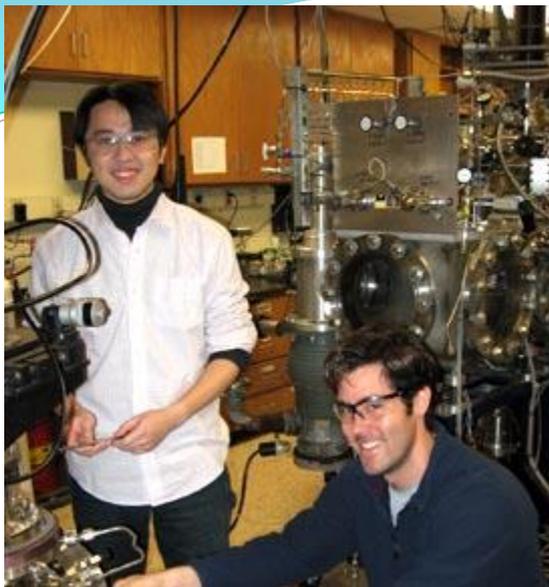


**Dave Flaherty**  
Ph.D. May 2010  
Asst. Professor  
Univ. of Illinois  
Urbana-Champaign

<http://www.scs.illinois.edu/flaherty/index.html>

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# Archive Catal. & Surf. Chem. Lab Photo-Gallery



**Wen-Yueh Yu and Dave Flaherty work on the "Baby" chamber (2010).**



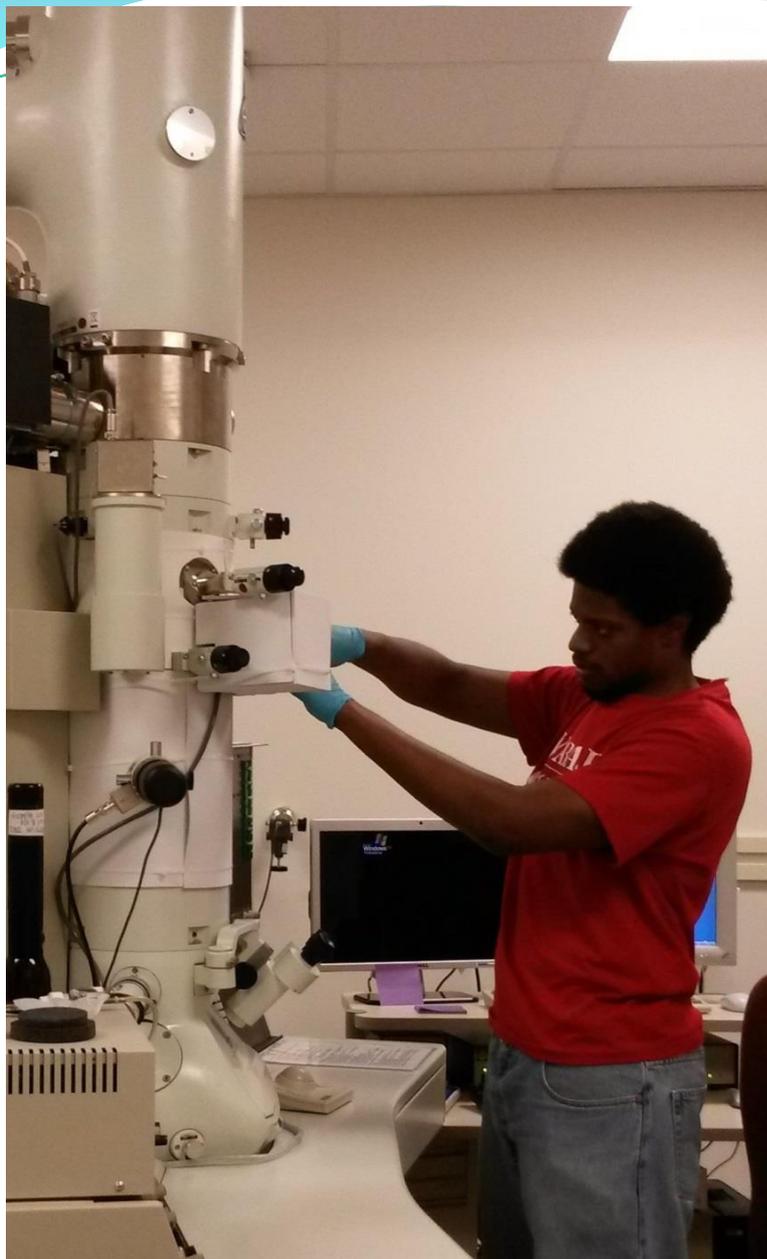
**Buddie Mullins and Dave Flaherty (2010).**



**Dave Flaherty and group at graduation mini-celebration (2010).**

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# Catal. & Surf. Chem. Lab Photo-Gallery II

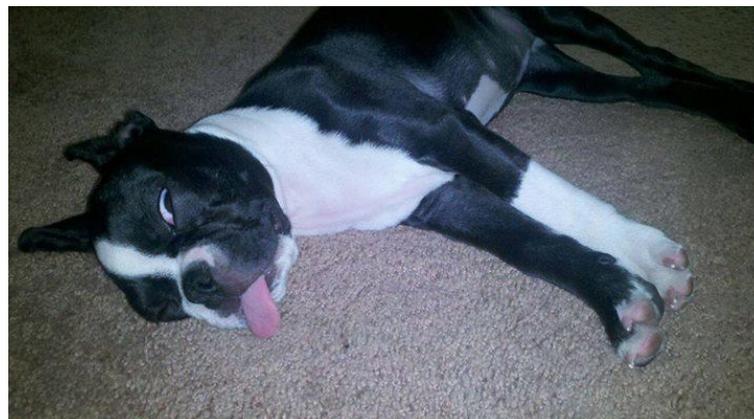


Edward Evans adjusting the TEM (2014).



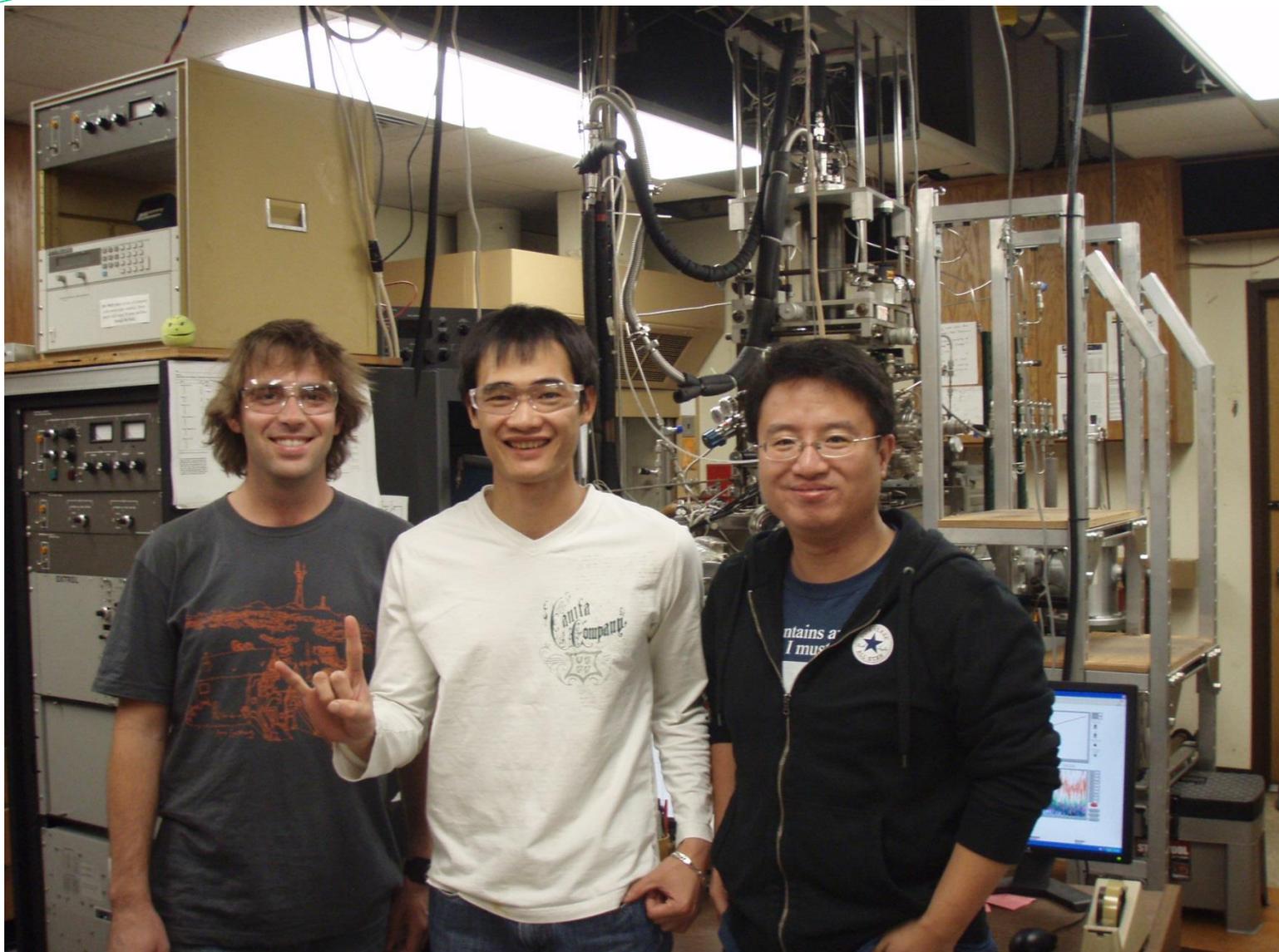
Greg Mullen in a light moment (2014).

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Greg Mullen's pup Mia taking a nap (2014).

# Archive Catal. & Surf. Chem. Lab Photo-Gallery III



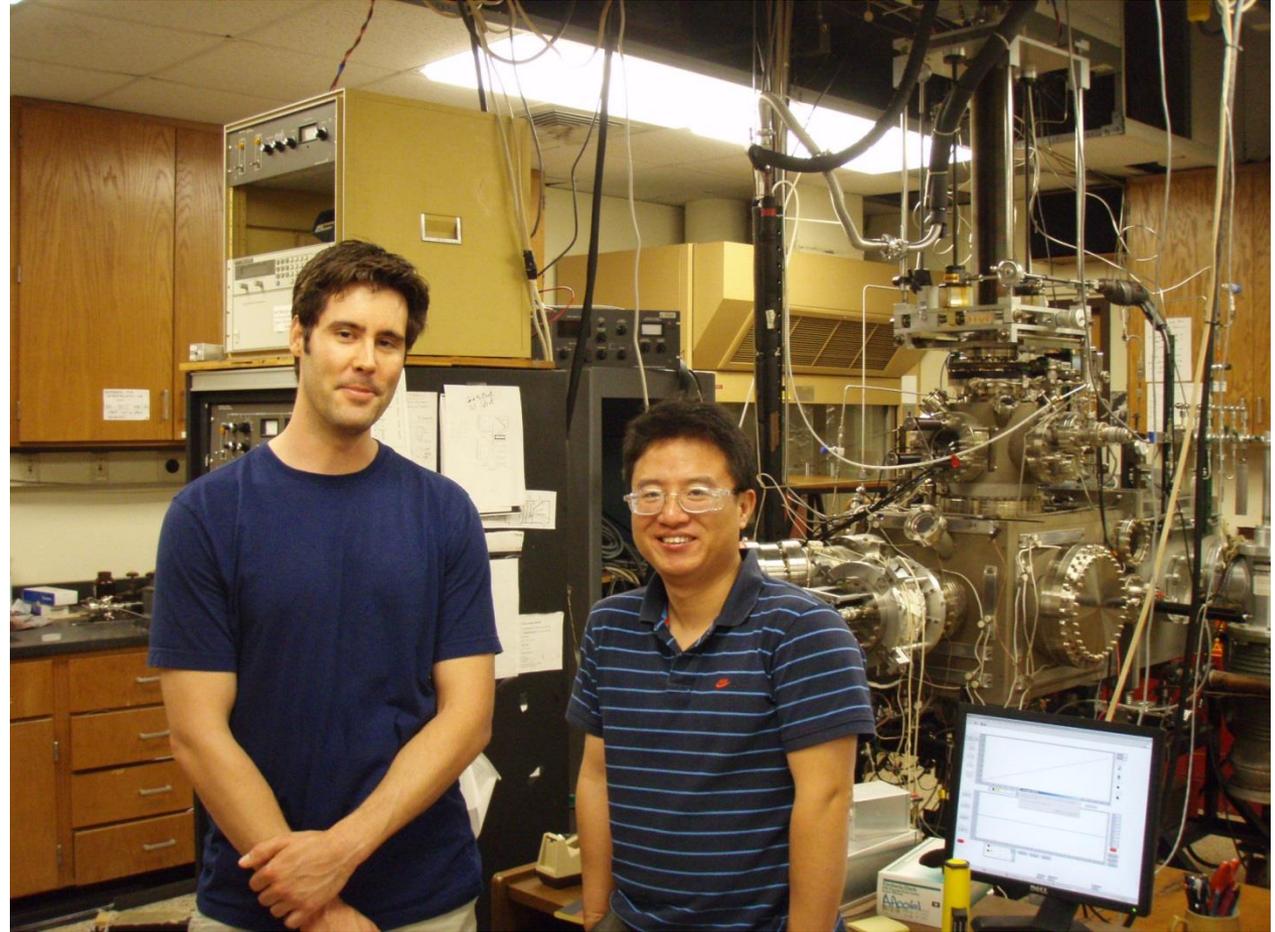
**Adrian Brush, Son Hoang, and Ming Pan with one of our Molecular Beam Surface Scattering Apparatus (2012).**

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# Archive Catal. & Surf. Chem. Lab Photo-Gallery IV



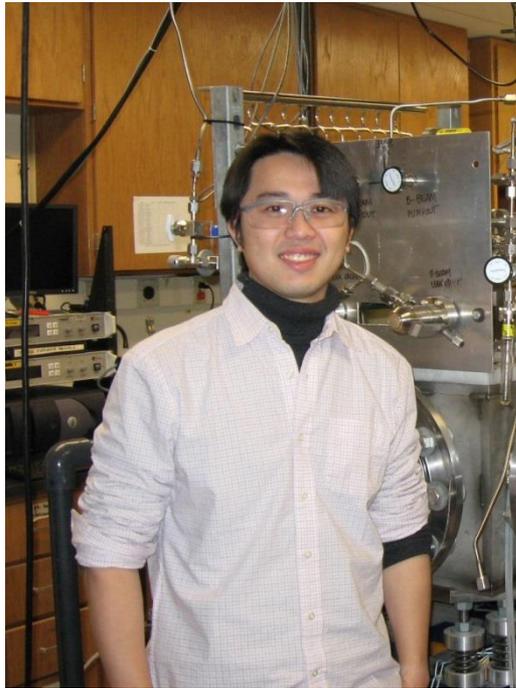
**Ming Pan tuning the quadrupole (2009).**



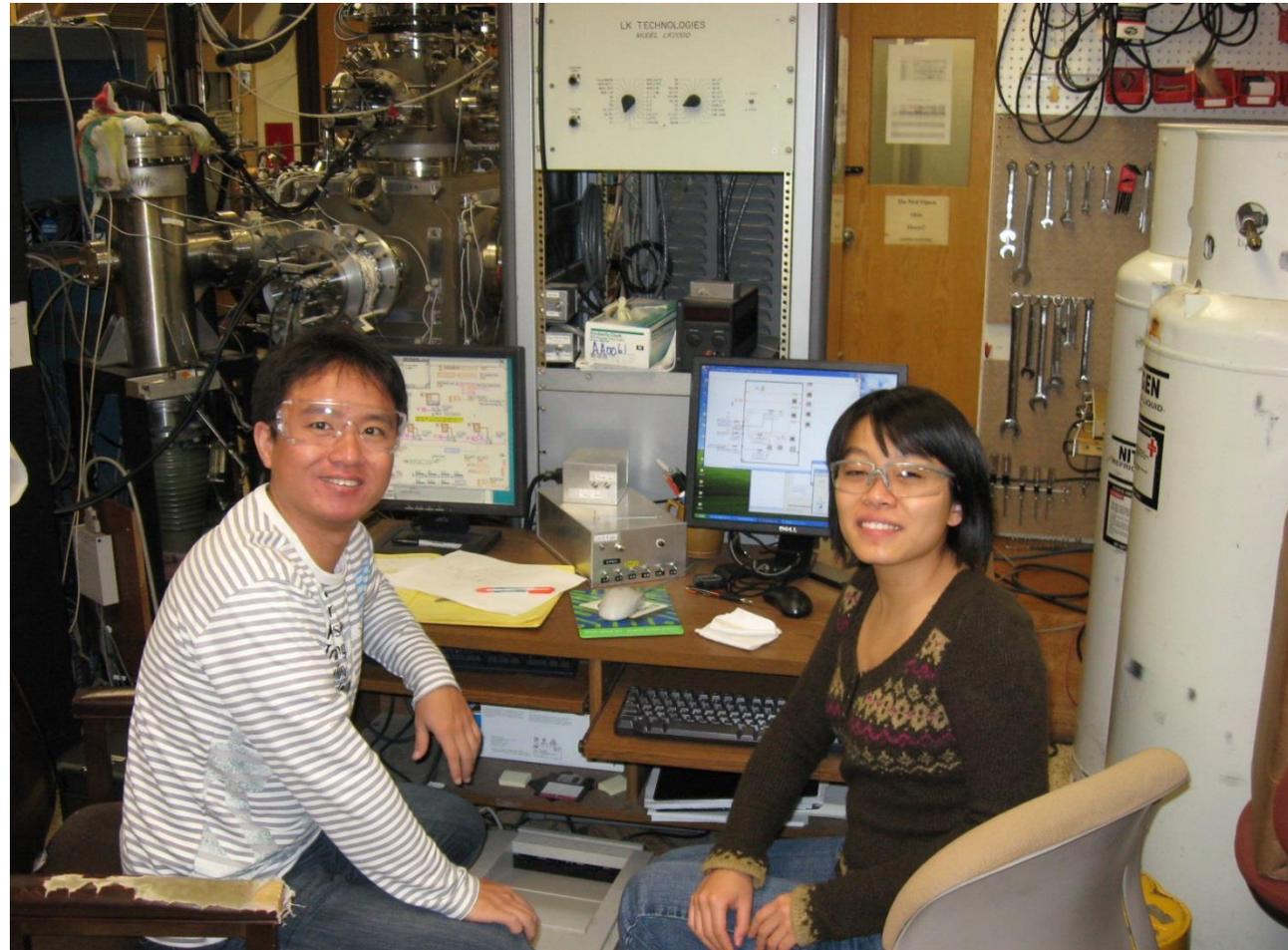
**Dave Flaherty and Ming Pan taking data (2010).**

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# Archive Catal. & Surf. Chem. Lab Photo-Gallery V

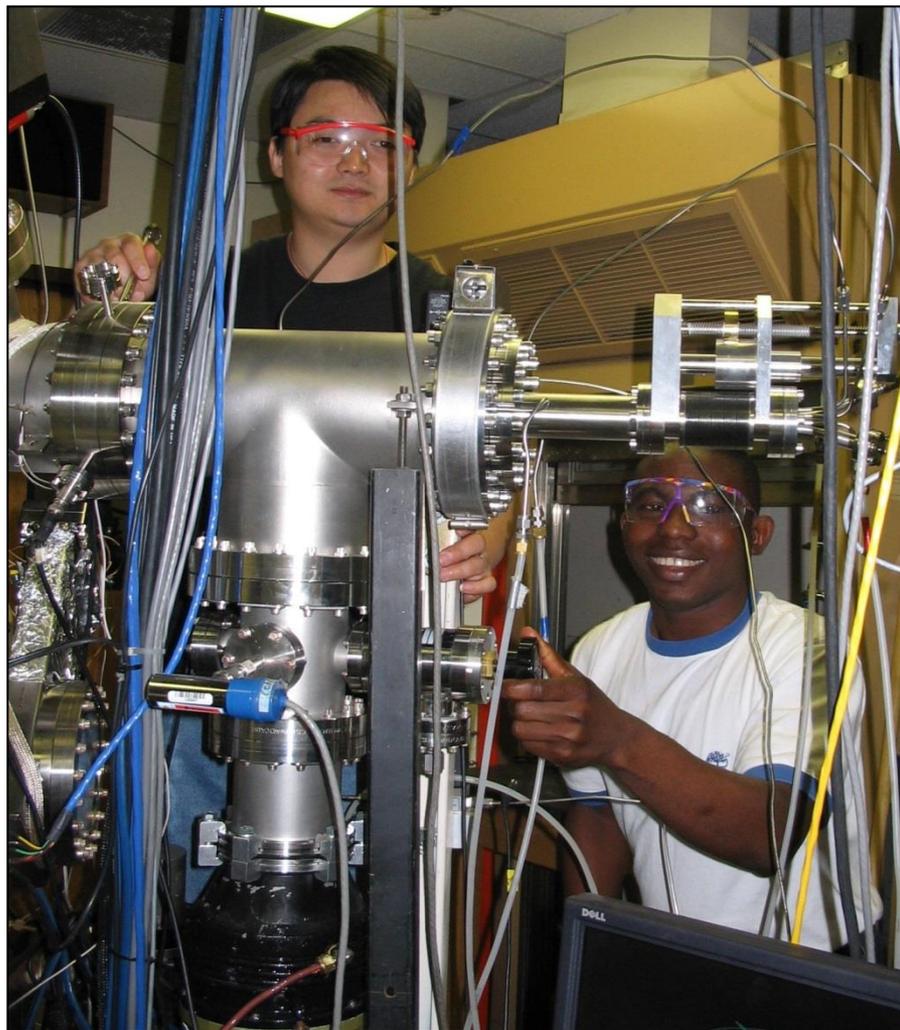


**Wen-Yueh Yu working  
in the lab (2010).**



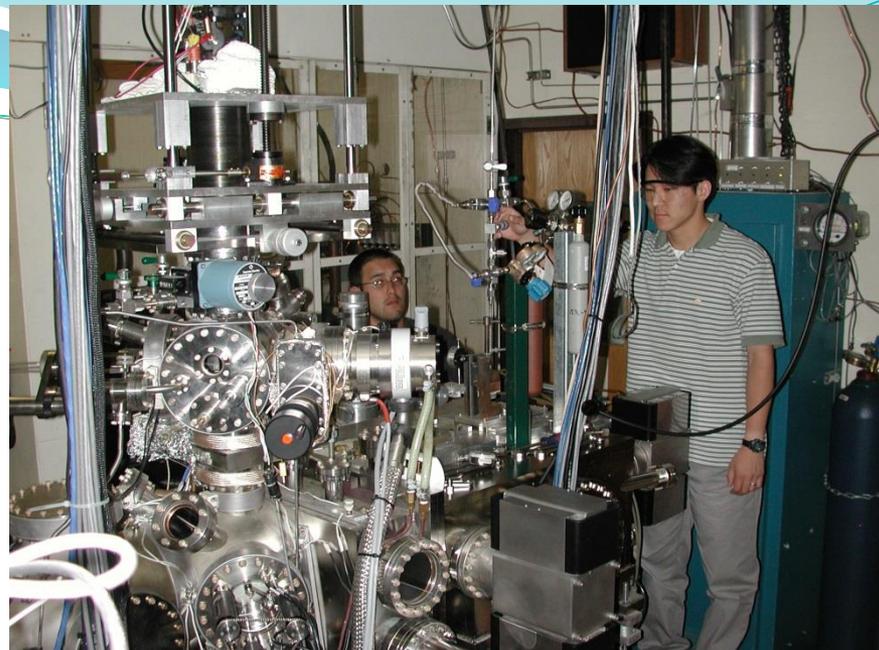
**Ming Pan and Ting Yan performing surface  
chemistry experiments (2011).**

# Archive Catal. & Surf. Chem. Lab Photo-Gallery VI

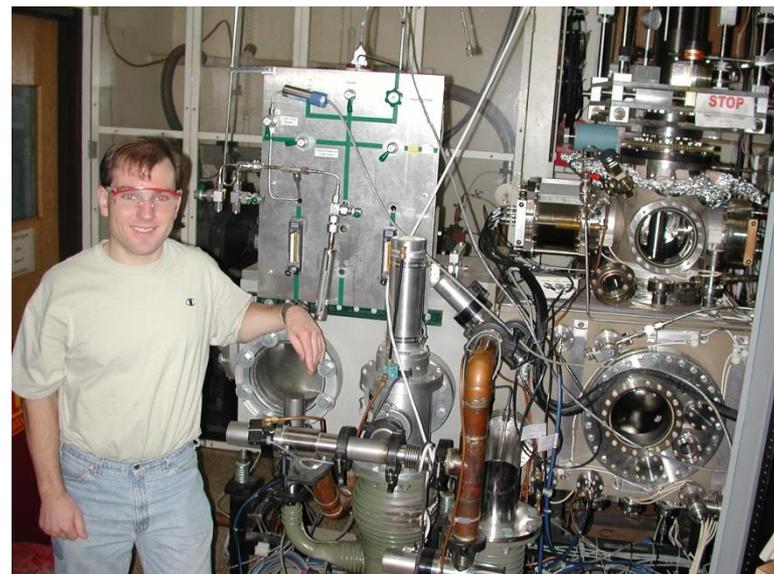


**Jinlong Gong and Rotimi Ojifinni adjusting their nanoparticle generator (2006).**

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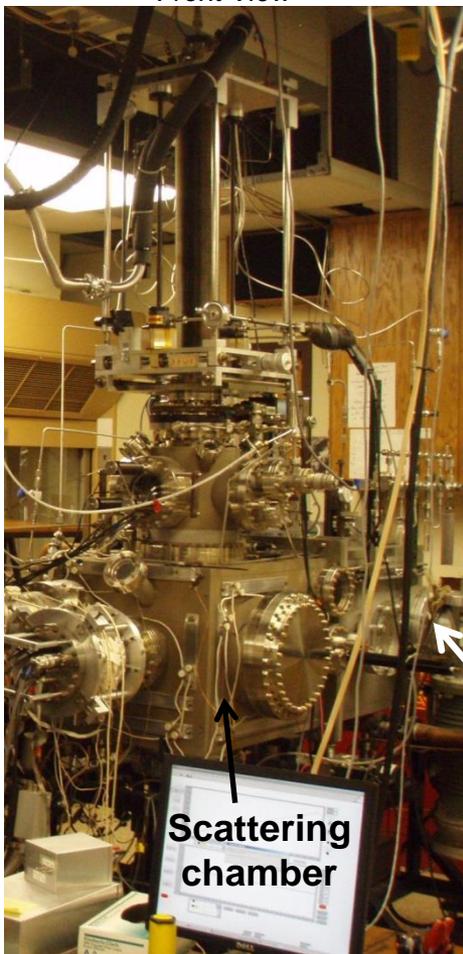
**James Stiehl and Tae Kim making measurements in the lab (2005).**



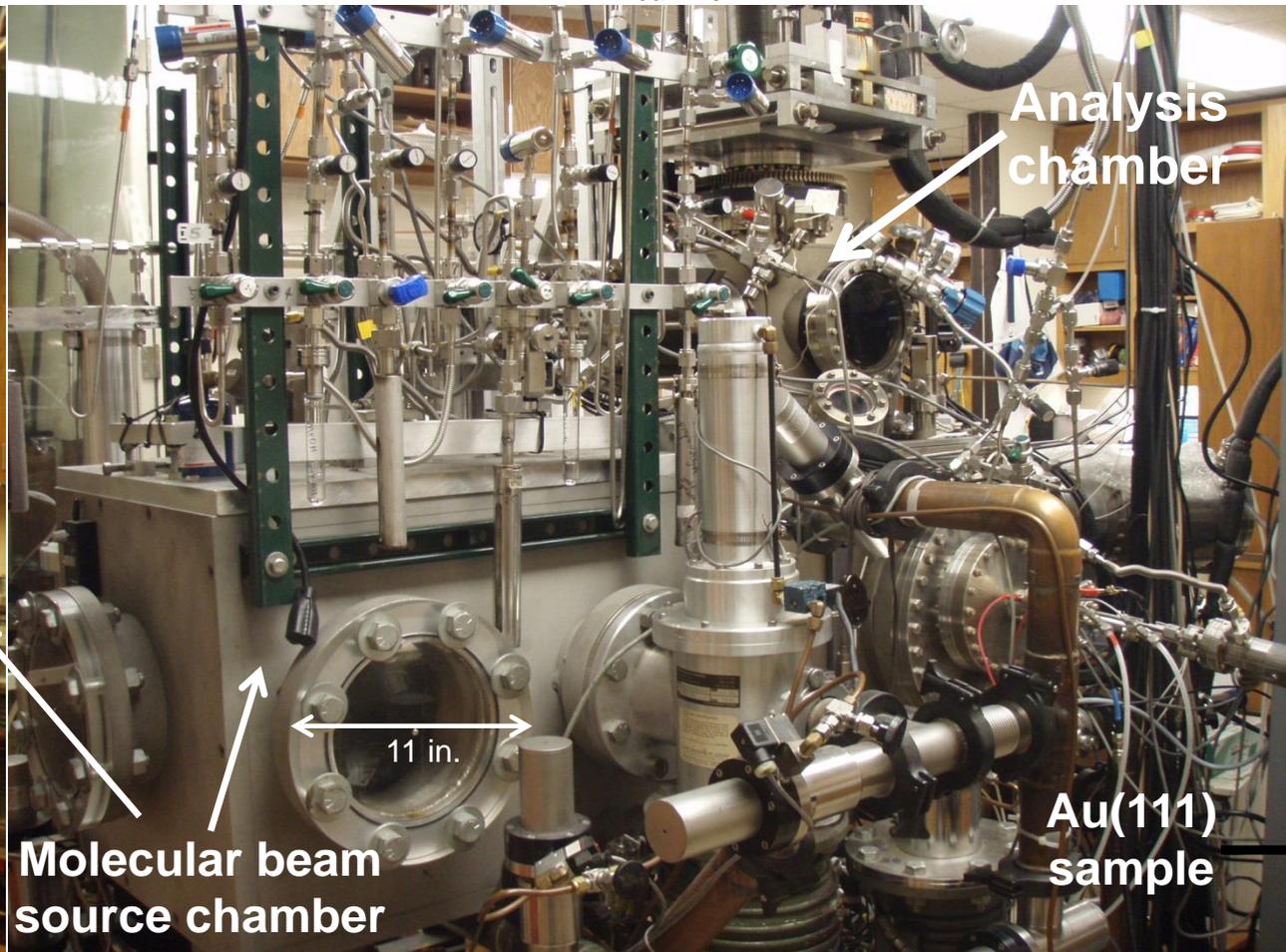
**Doug Safarik with his machine (2003).**

# Archive Catal. & Surf. Chem. Lab Photo-Gallery VII

Front View



Rear View



Close up of one of our ultrahigh vacuum surface chemistry machines.

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# Mullins Research Group Photo – April 2014



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