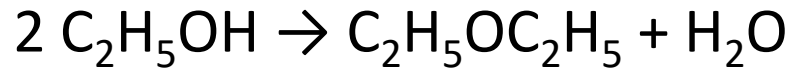


HW3: Ethanol dehydration over 192 mg of Al-SiO₂ catalyst, gas phase, fixed bed reactor, 240 °C



Feed: 4.4 mol% ethanol, the rest being flowing N₂ (40 cm³ min⁻¹ @STP)

Analysis of the products by GC-FID:

2.326 mol% ethylene, 0.332 mol% diethylether, water from dehydration rxn, ethanol 1.553 mol%, the rest being N₂ (constant)

Calculate conversion, selectivity to ethylene and diethylether + their yields. Calculate carbon balance. Calculate WHSV.

Heterogeneous catalysis (C9981)

Lecture 4

Catalysts preparation – continuation

- Shaping
- Single site catalysts

styskalik@chemi.muni.cz

styskalik.sci.muni.cz

Heterogeneous catalysis

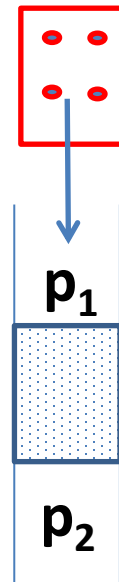
Lecture 4

Catalyst synthesis – continuation

- Shaping
- Single site catalysts

Shaping

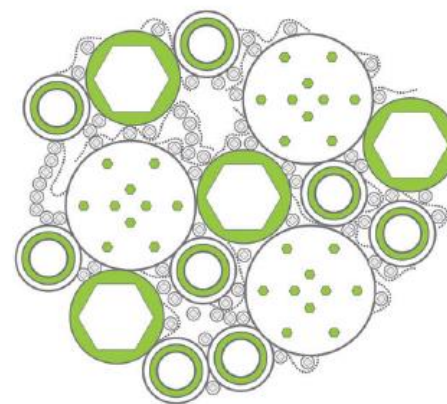
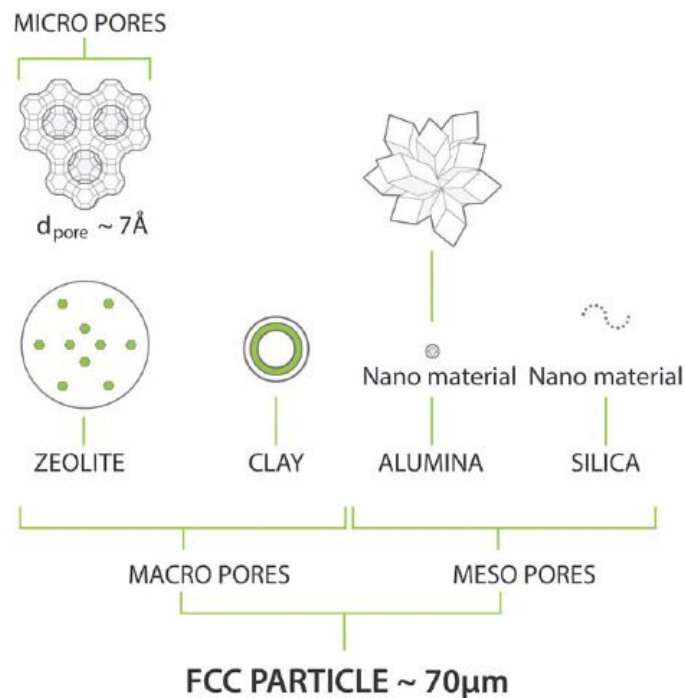
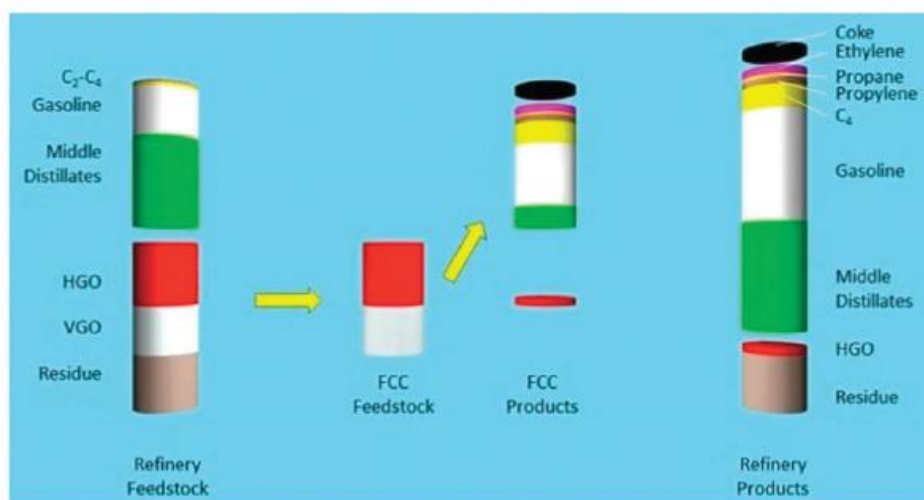
- Why is shaping important?
 - Accessibility
(micro+meso+macro porosity)
 - Mechanical resistance
(application of binders)
 - Reducing pressure drop
($p_1 > p_2$)
 - Hydrothermal stability, coking, poisoning,...



→ **Industrial point of view**

Shaping

- Industrial example:
Fluid catalytic cracking



Shaping

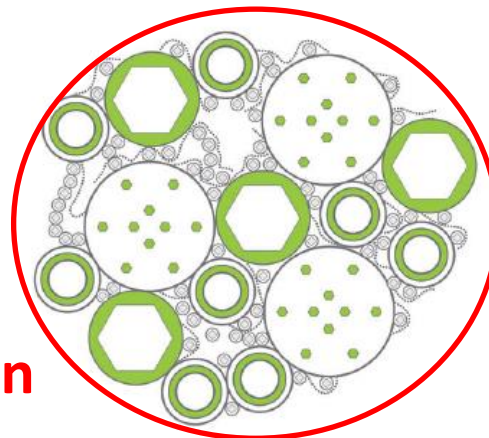
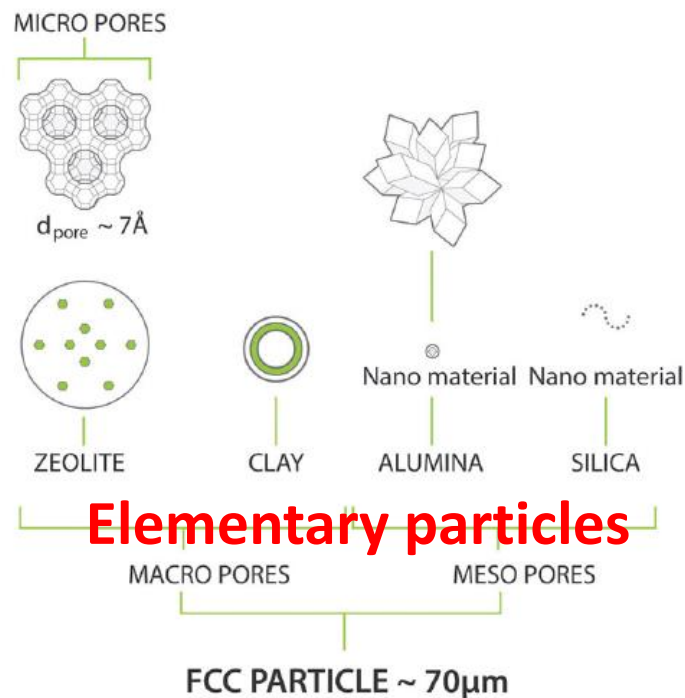
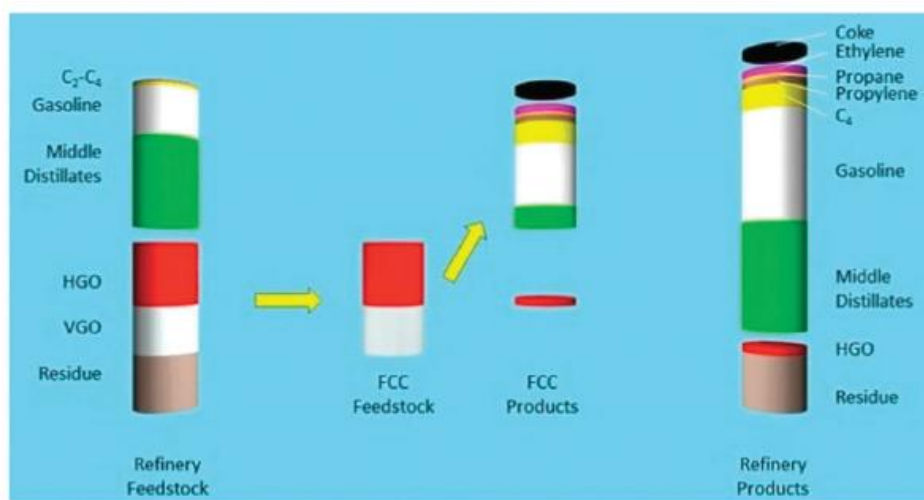
- Fluid catalytic cracking

The above demands can be met in a catalyst system that combines a number of components, as depicted in Fig. 7. As described above, the main active component is a zeolite, usually a stabilized form of zeolite Y. This material contains an internal porous structure in which acid sites are present, which can convert larger molecules to the desired gasoline range molecules. Clay is added as filler, but also for heat-capacity reasons. Various alumina and silica sources are used to produce a meso- and macroporous matrix that allows access to, and pre-cracks the larger molecules in the feedstocks. In addition, these components are used to bind the system together. Additional components may comprise specific metal traps for trapping Ni and V. The components are typically mixed in aqueous slurry, and then spray-dried to form more or less uniform spherical particles that can be fluidized in the regenerator.

„agglomerated catalyst“

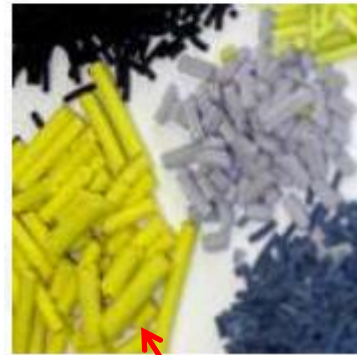
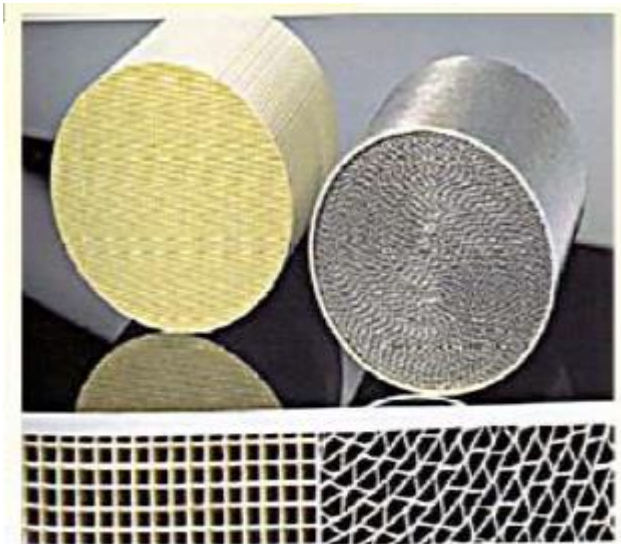
Shaping

- Industrial example:
Fluid catalytic cracking



Shaping

- Macroscopic shaping
 - Extrusion
 - Pelletization
 - Molding/casting



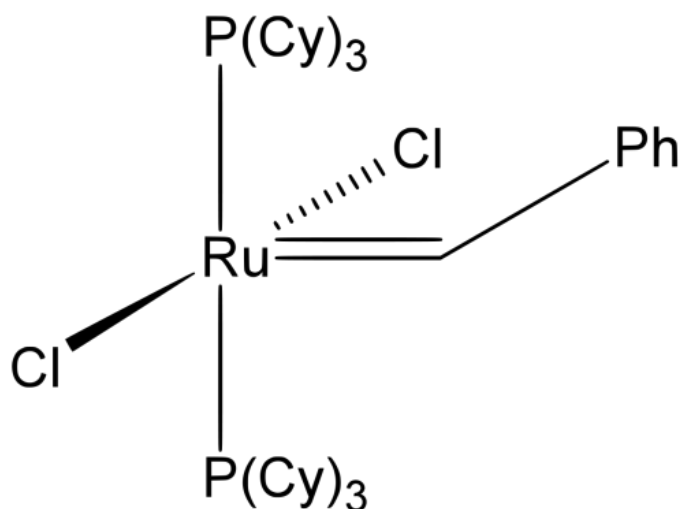
grain

Shaping

- Shaping as a „mechanochemical synthesis“?

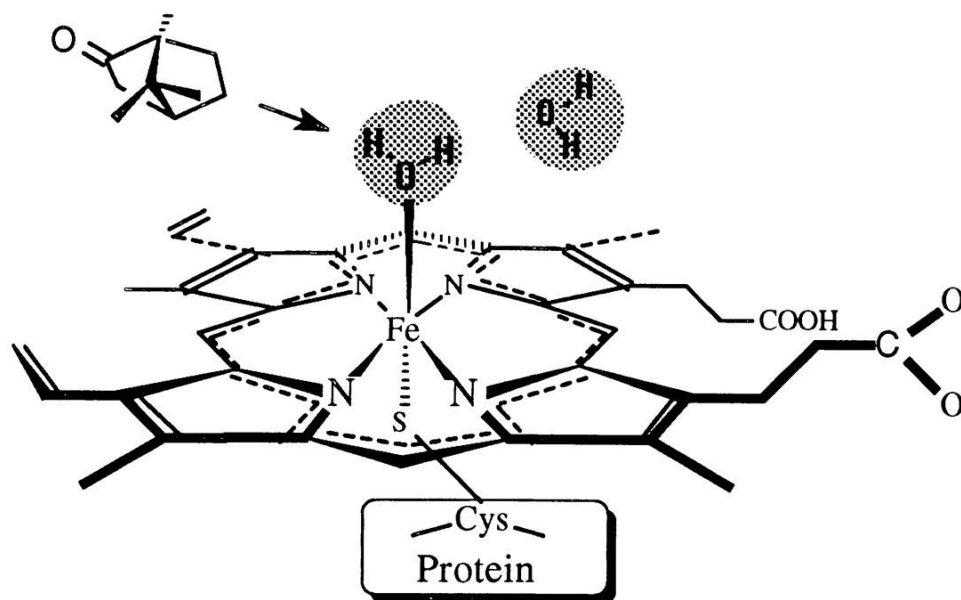
Single site catalysts

- What is it?



Grubbs catalyst

Homogeneous catalysis

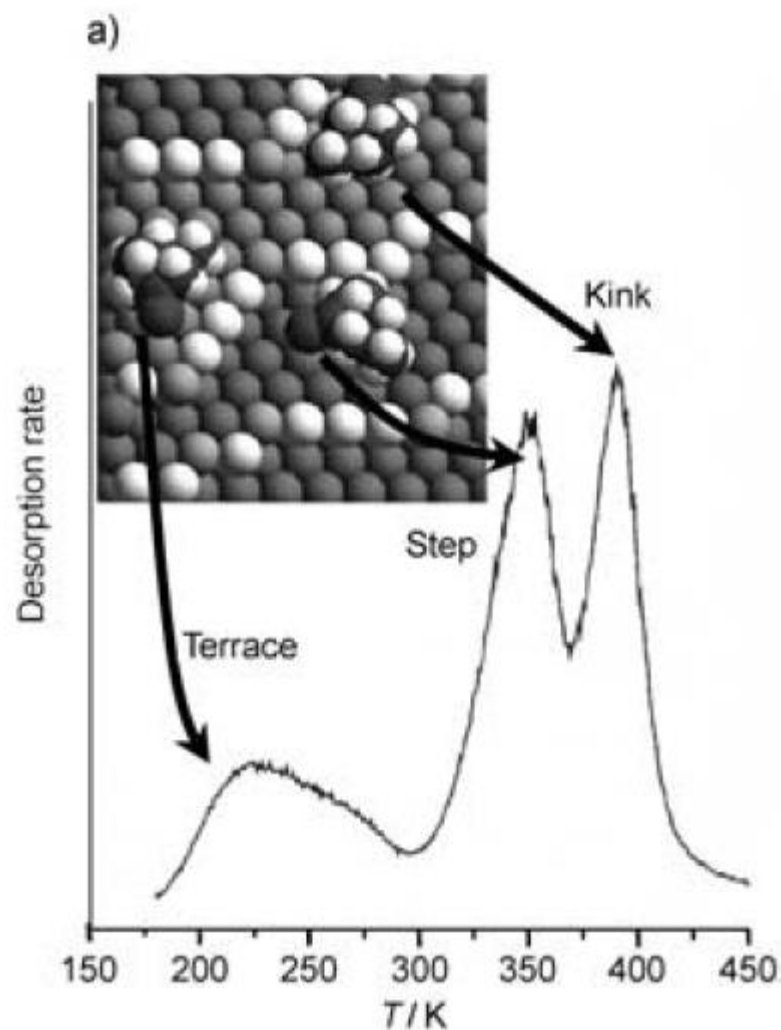
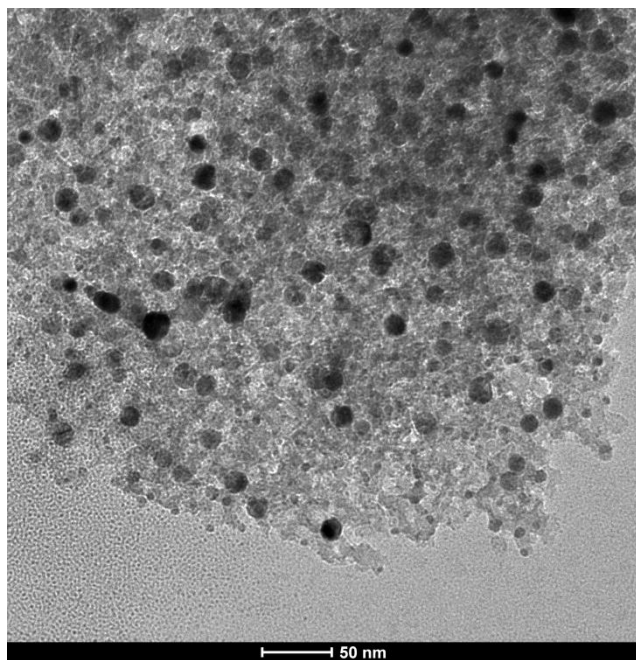


Active site in cytochrome P450

Enzymatic catalysis

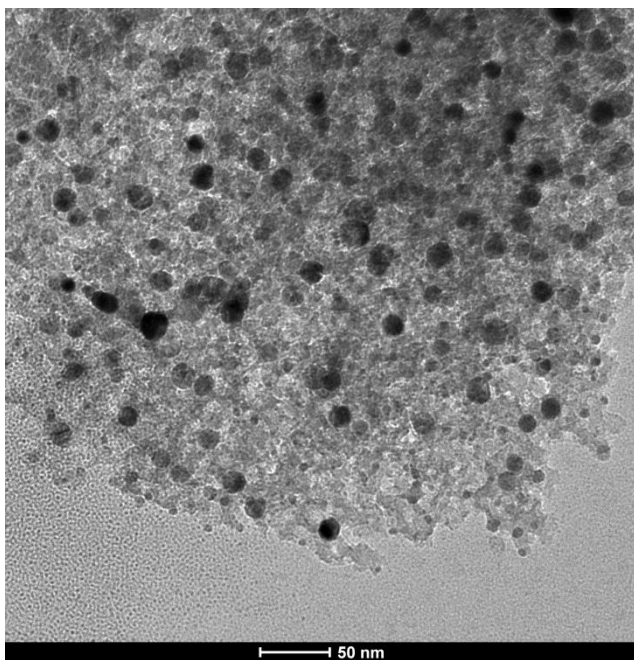
Single site catalysts

- What is it?

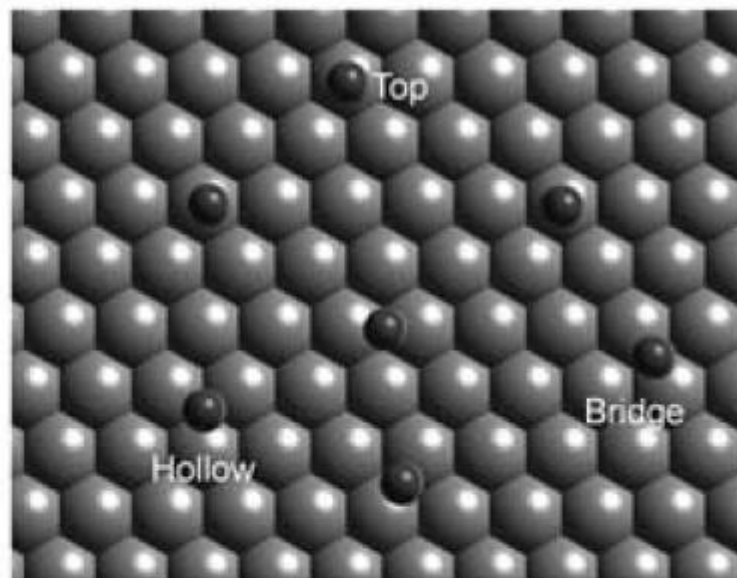


Single site catalysts

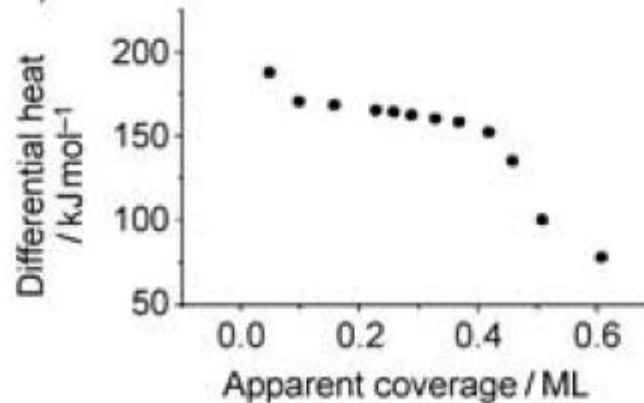
- What is it?



b)



c)



Single site catalysts

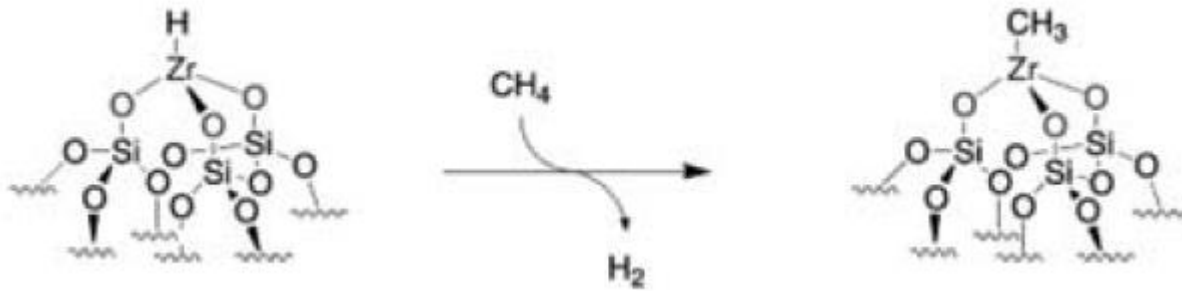
- Any continuous material (metal, oxide), where catalysis relies mainly on structure defects
- Instead
 - One (or more) atoms
 - Spatially isolated
 - Same energy of interaction with reactant
 - Structurally well characterized (similar to homo)

Single site catalysts

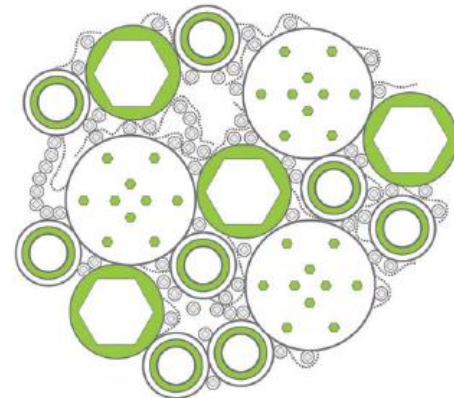
- What is it?
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 - Crystalline, open-structure, microporous solids (e.g. zeolites) with active sites uniformly distributed throughout the bulk

Single site catalysts

- Why?



FCC PARTICLE ~ 70 μ m

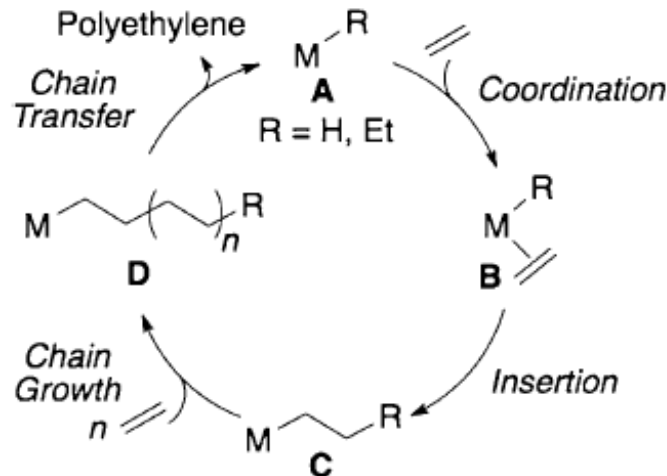


Single site catalysts

- Why?
 - Number of active sites
 - Turn-over frequency, TOF
 - Characterization of active site
 - Quantum-chemical calculations
 - ↓
 - Understanding mechanism
 - Understanding kinetics
 - ↓
 - Bridging gap between homo-and heterogeneous cata

Single site catalysts

- Bridging gap between homogeneous and heterogeneous catalysis – **example:**
 - Phillips catalyst = „CrO₃“ dispersed on silica
 - Ethylene polymerization (50 % of global production of linear HDPE)
 - No co-catalyst (compare with Ziegler-Natta + MAO)
 - What is the actual active site???



Single site catalysts

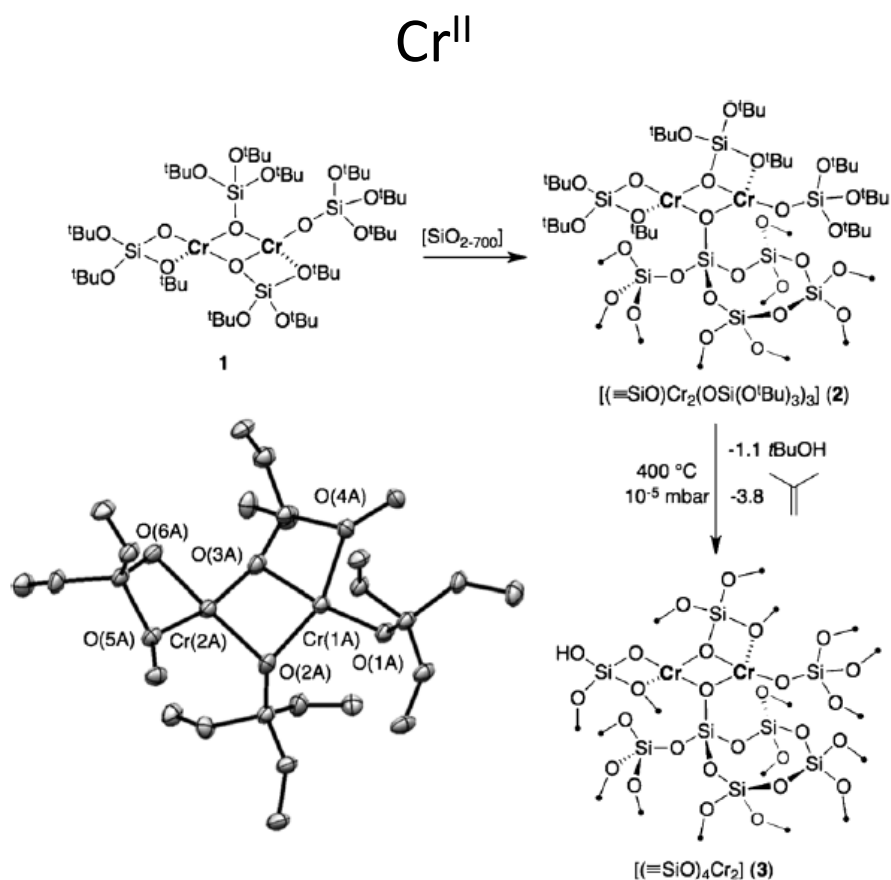
- CrO_3 dispersed on silica
- Ethylene exposure induces „mild reduction“
- Only 10 % of Cr sites are active

- **Cr^{II} or Cr^{III} ???** Big discussion...

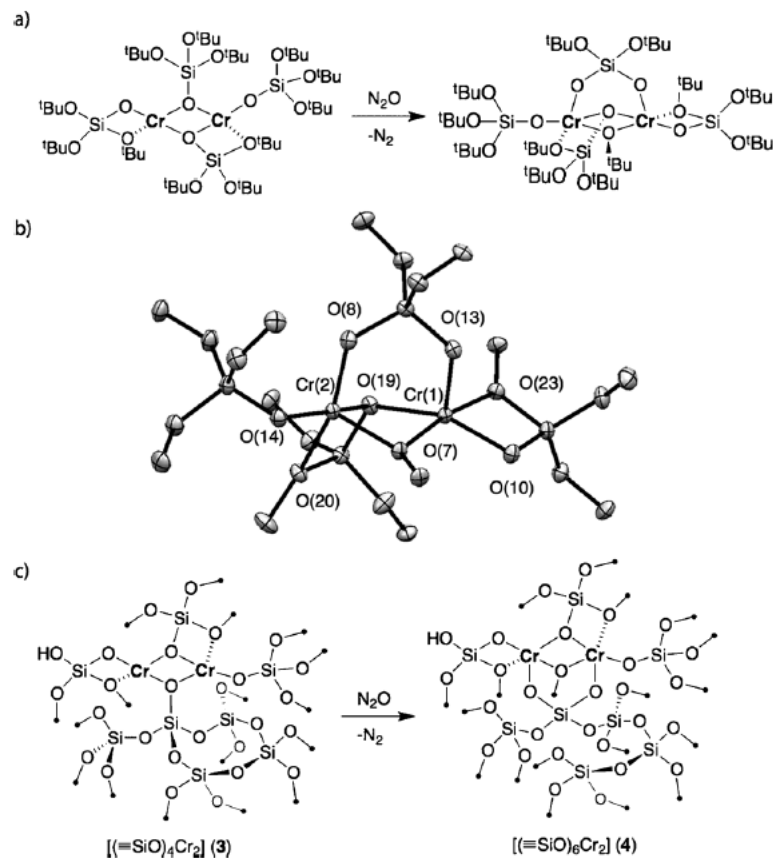
Polymerization of Ethylene by Silica-Supported Dinuclear Cr^{III} Sites through an Initiation Step Involving C–H Bond Activation

*Matthew P. Conley, Murielle F. Delley, Georges Siddiqi, Giuseppe Lapadula, Sébastien Norsic, Vincent Monteil, Olga V. Safonova, and Christophe Copéret**

Single site catalysts



Scheme 2. Grafting of **1** on SiO_{2-700} to form $[(\equiv\text{SiO})\text{Cr}_2(\text{OSi}(\text{O}^t\text{Bu})_3)_3]$ (**2**) and thermal decomposition under high vacuum to yield $[(\equiv\text{SiO})_4\text{Cr}_2]$ (**3**). The solid-state structure obtained by X-ray diffraction for an independent molecule of **1** is shown at 50% probability. Methyl groups of $-\text{OSi}(\text{O}^t\text{Bu})_3$ ligands and H atoms have been removed for clarity.



Scheme 3. a) Reaction of **1** with N_2O to give **5**. b) Solid-state structure of **5** as obtained by X-ray diffraction. Methyl groups of $-\text{OSi}(\text{O}^t\text{Bu})_3$ ligands and H atoms have been removed for clarity. c) Surface rearrangement of $[(\equiv\text{SiO})_4\text{Cr}_2]$ (**3**) to form $[(\equiv\text{SiO})_6\text{Cr}_2]$ (**4**).

Single site catalysts

Cr^{III} is active!

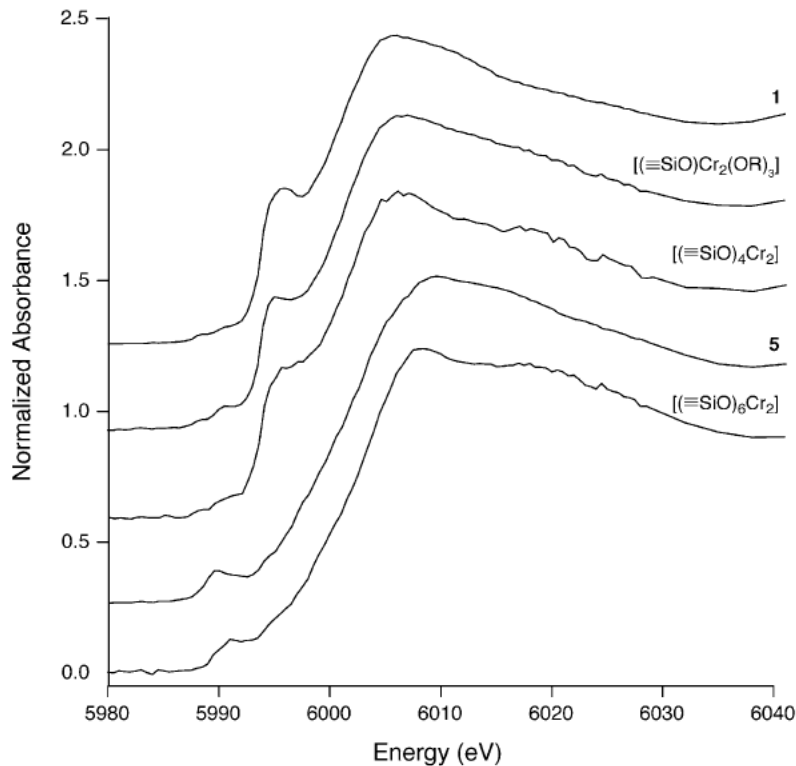
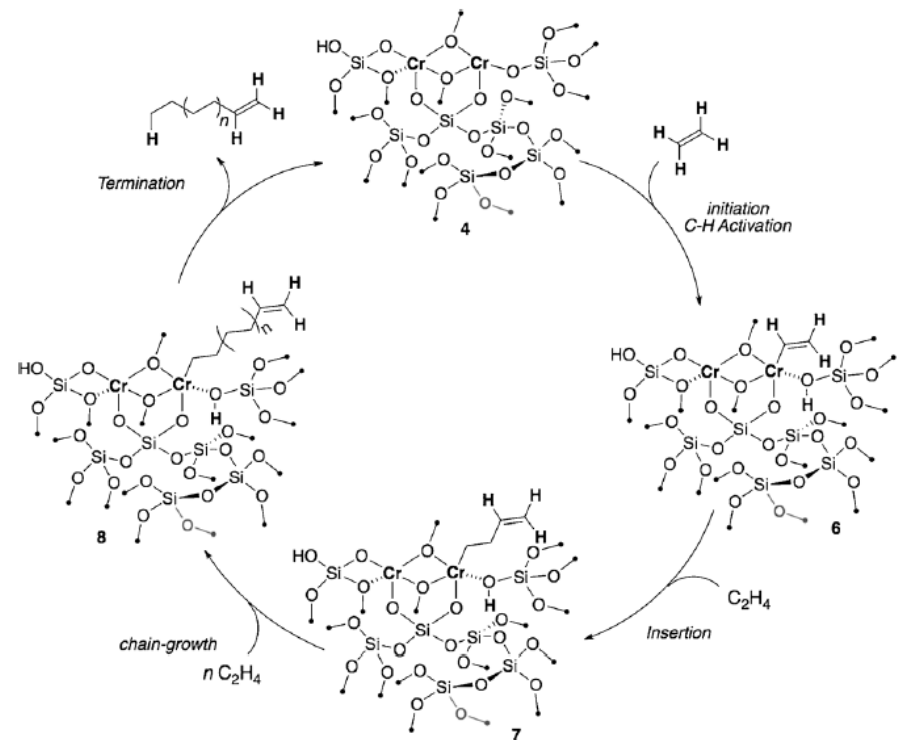


Figure 1. XANES spectra (collected in the transmission mode) of 1, $[(\equiv\text{SiO})\text{Cr}_2(\text{OSi}(\text{O}t\text{Bu})_3)_3]$ (2), $[(\equiv\text{SiO})_4\text{Cr}_2]$ (3), $[(\equiv\text{SiO})_6\text{Cr}_2]$ (4), and 5.



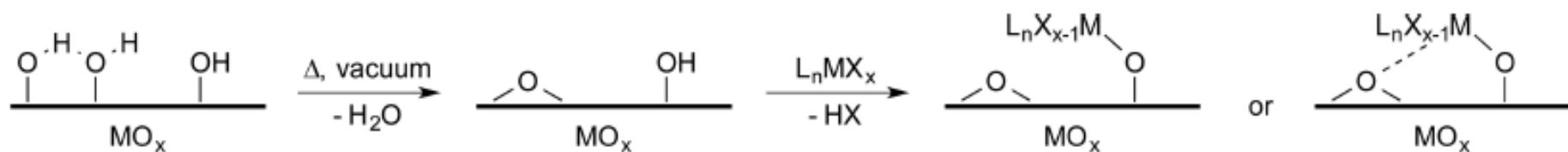
Scheme 4. Proposed mechanism for ethylene polymerization by $[(\equiv\text{SiO})_6\text{Cr}_2]$.

Single site catalysts

- What is it?
 - **Individual isolated ion/atom/molecular complex/cluster**
 - **Grafted on porous support**
 - Created within the material by building block approach
 - „Ship in bottle“ structures– e.g. molecular complex/enzyme trapped within a zeolitic cage
 - Crystalline, open-structure, microporous solids (e.g. zeolites) with active sites uniformly distributed throughout the bulk

Single site catalyts

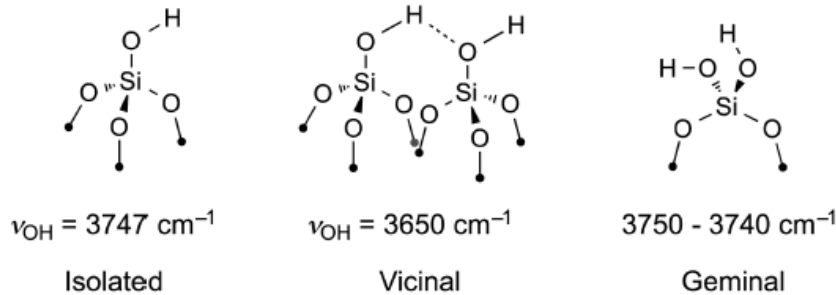
- Grafting on silica



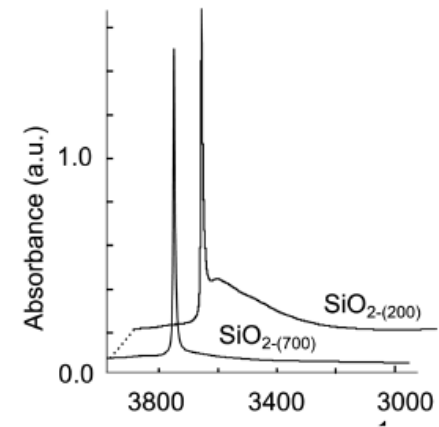
- Detailed knowledge of surface (number of OH groups per nm²)
- Rigorous water- and oxygen-free environment

Single site catalysts

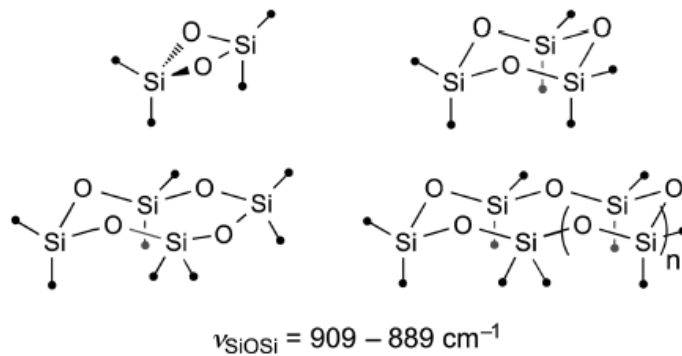
a) Types of silanols



b) IR spectra



c) Siloxane Rings



d) OH density as a function of T

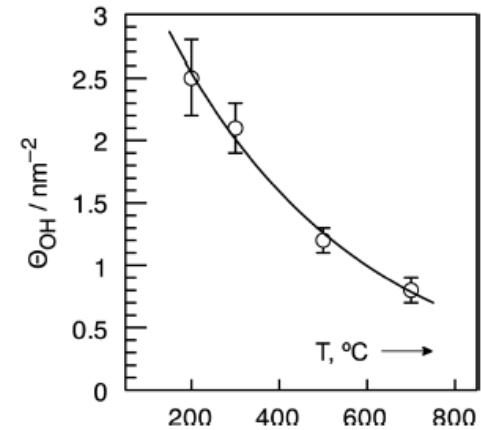


Figure 4. (a) Types of silanols. (b) Infrared spectra of Aerosil-200 partially dehydroxylated at 200 and 700 °C ($\text{SiO}_2-(200)$ and $\text{SiO}_2-(700)$). (c) Siloxane rings. (d) Effect of temperature on surface OH density.

Single site catalysts

- Metal precursors (almost all d + f elements)
 - Organometallic compounds
 - Metal amides and silylamides
 - Metal alkoxides and siloxides
 - Metal halogenides

**CHEMICAL
REVIEWS**

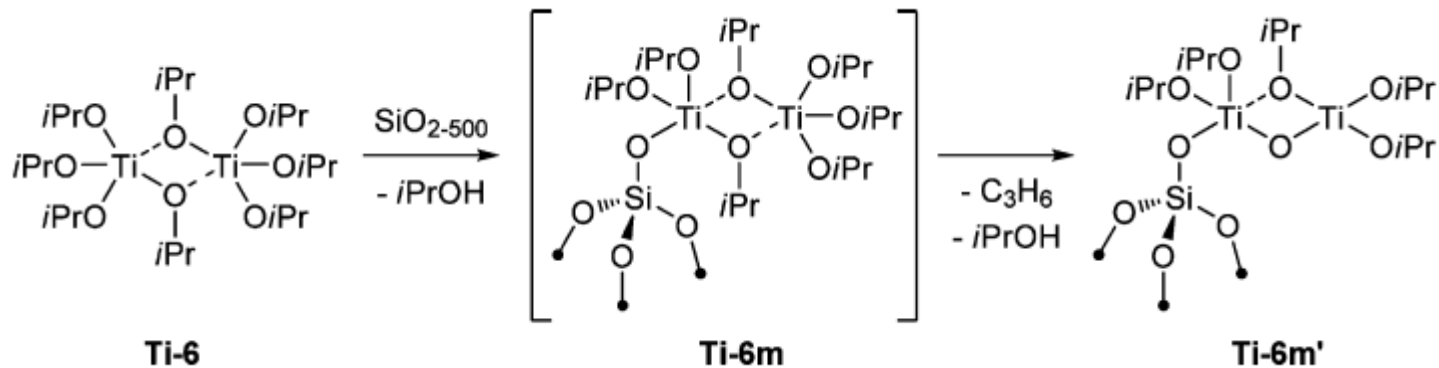
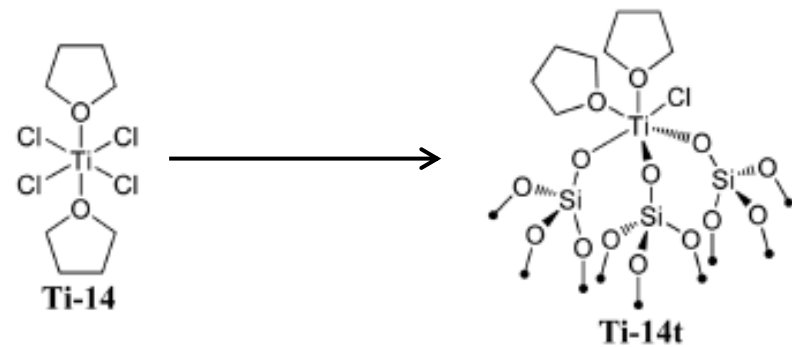
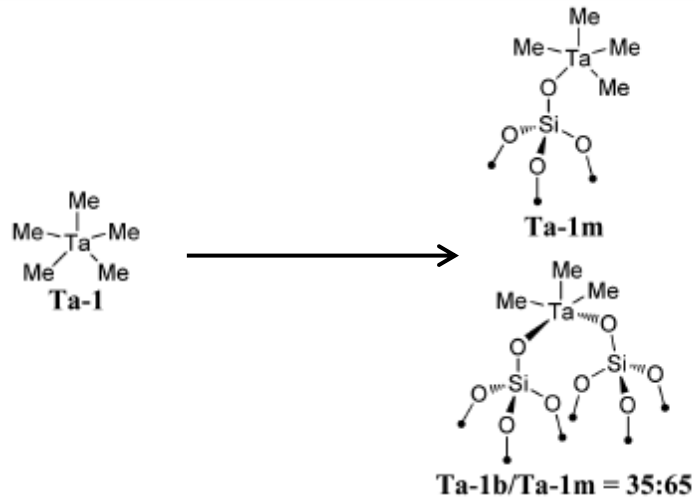
Review

pubs.acs.org/CR

Surface Organometallic and Coordination Chemistry toward Single-Site Heterogeneous Catalysts: Strategies, Methods, Structures, and Activities

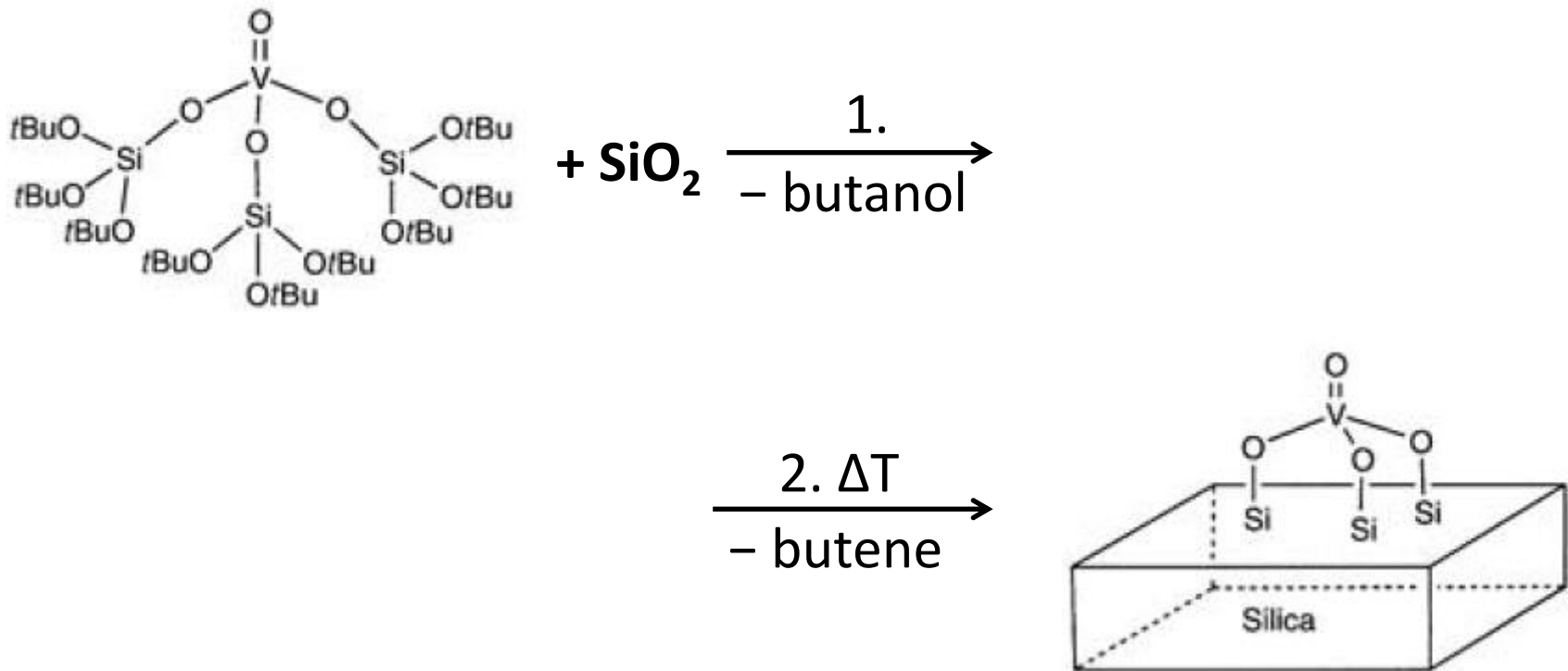
Christophe Copéret,^{*,†} Aleix Comas-Vives,[†] Matthew P. Conley,[†] Deven P. Estes,[†] Alexey Fedorov,[†] Victor Mougel,[†] Haruki Nagae,^{†,‡} Francisco Núñez-Zarur,[†] and Pavel A. Zhizhko^{†,§}

Single site catalysts



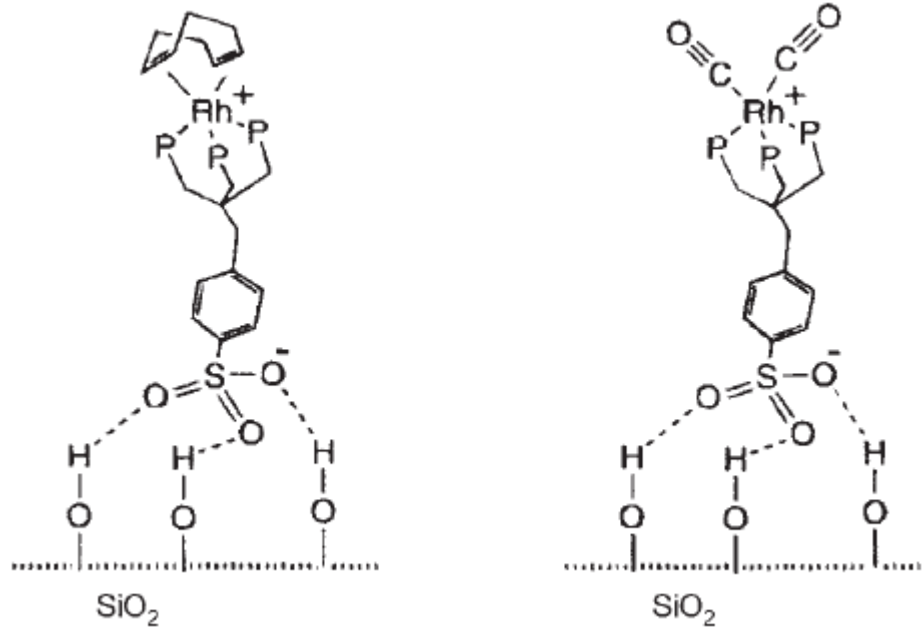
Single site catalysts

- In many cases silica needed all around the active site (no unreacted chlorines etc.)



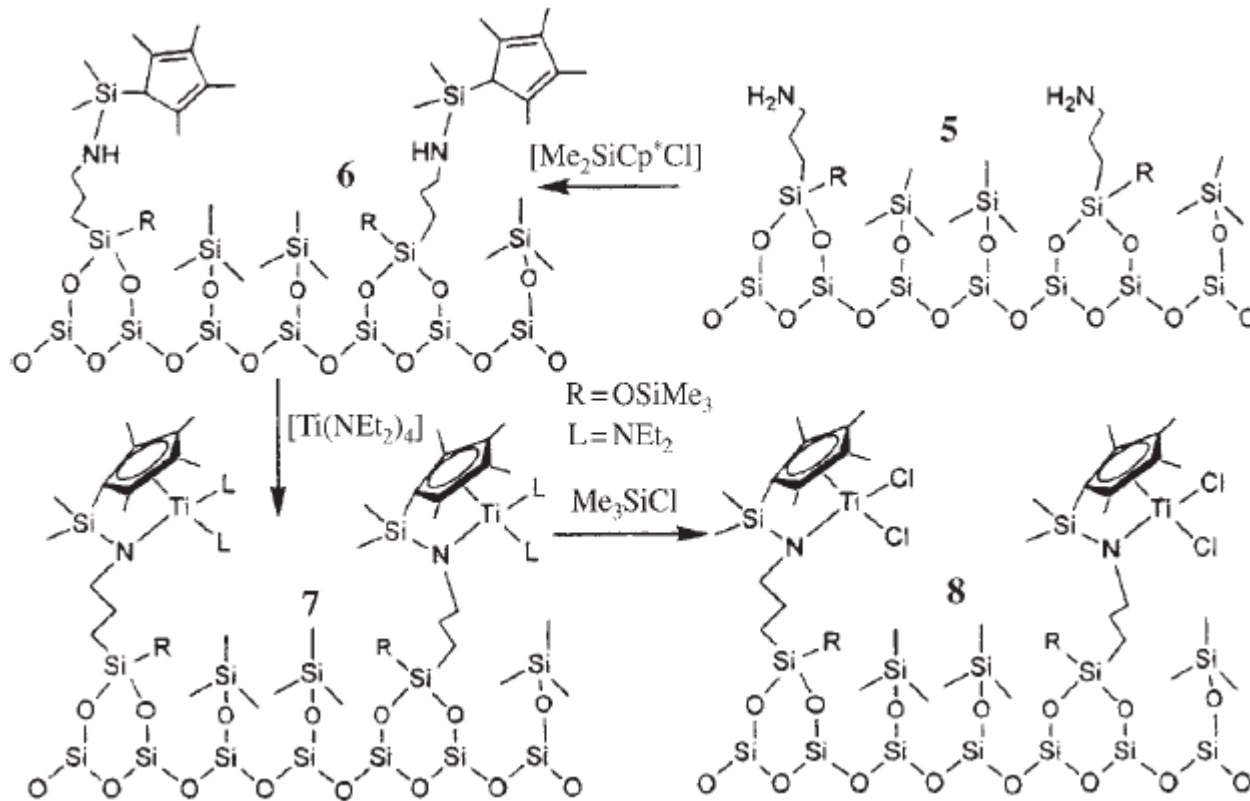
Single site catalysts

- Grafting on silica – other types of bonding



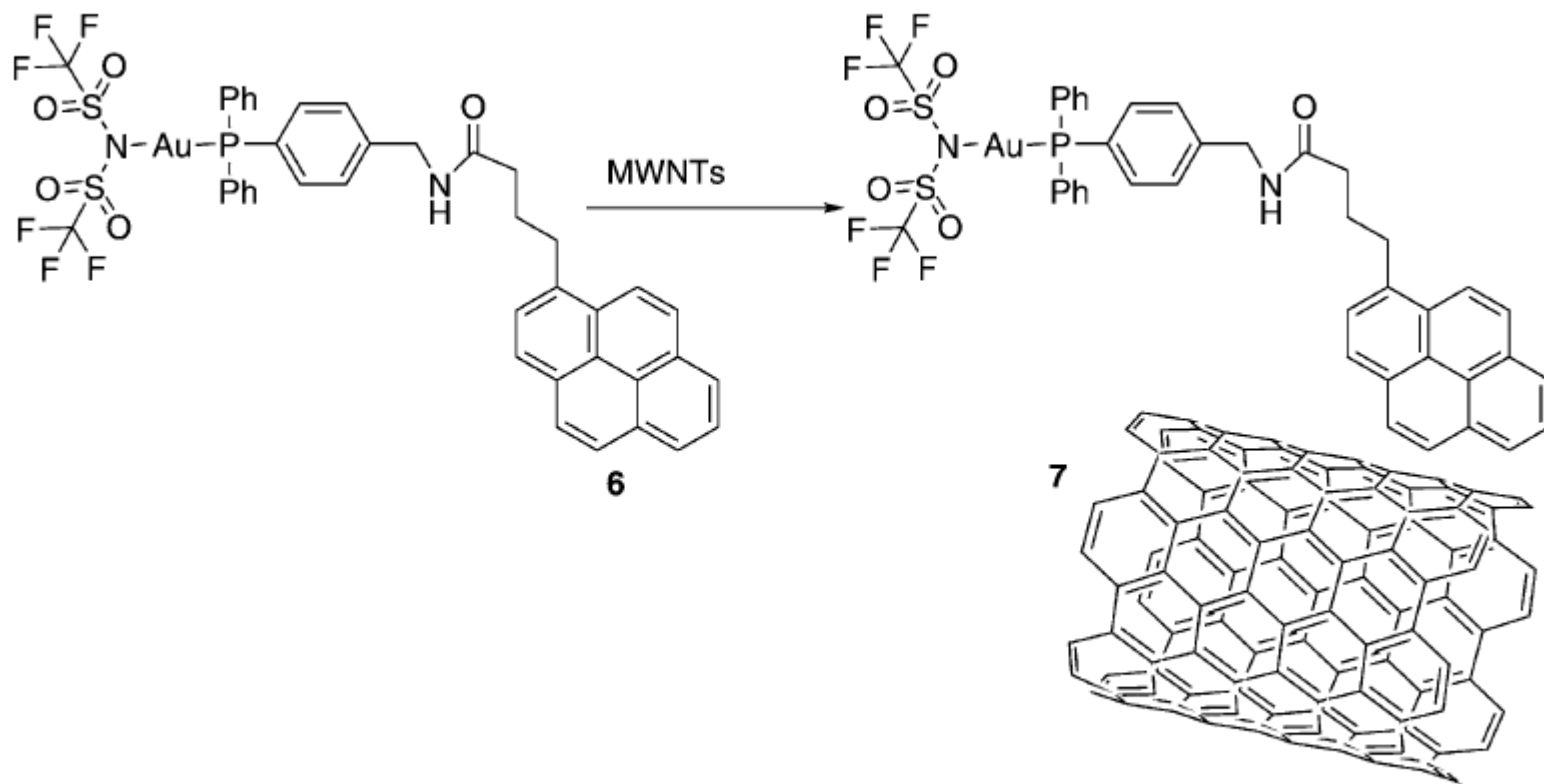
Single site catalysts

- Grafting on silica – other types of bonding



Single site catalysts

- Grafting on carbon – π - π stacking



Scheme 3. Incorporation of the pyrene-tagged gold complex 6 onto MWNTs.

Single site catalysts

- Grafting on carbon – π - π stacking
 - Boomerang effect

Conclusion

A pyrene-tagged gold complex has been designed for immobilisation onto MWNTs through π - π interactions to give a supported homogeneous “boomerang” catalyst. This catalyst remained intact on the CNT surface after immobilisation

Catalysis with Gold Complexes Immobilised on Carbon Nanotubes by π - π Stacking Interactions: Heterogeneous Catalysis versus the Boomerang Effect

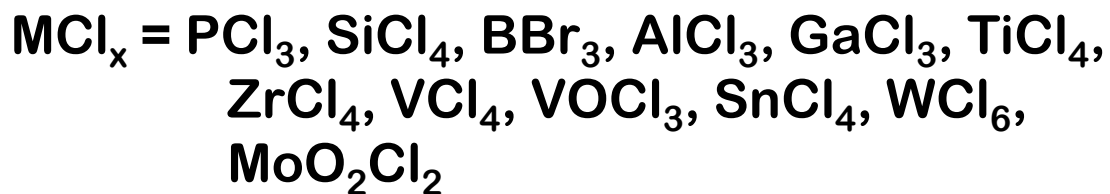
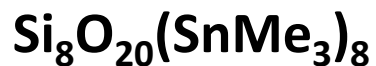
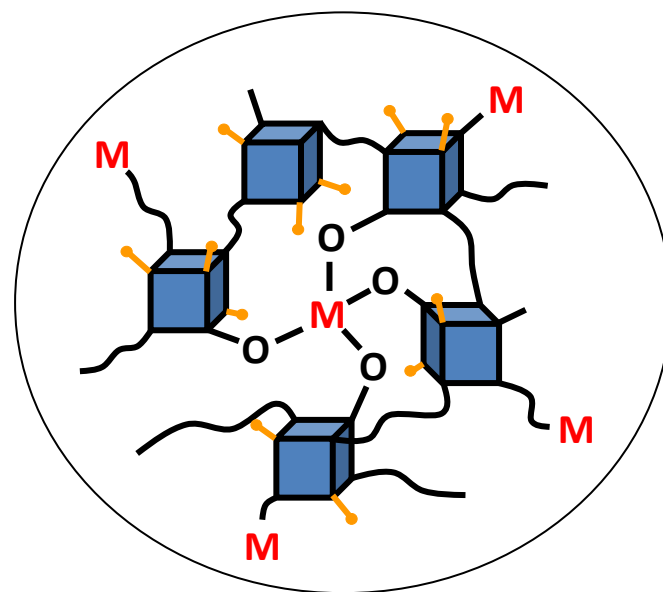
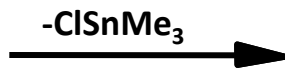
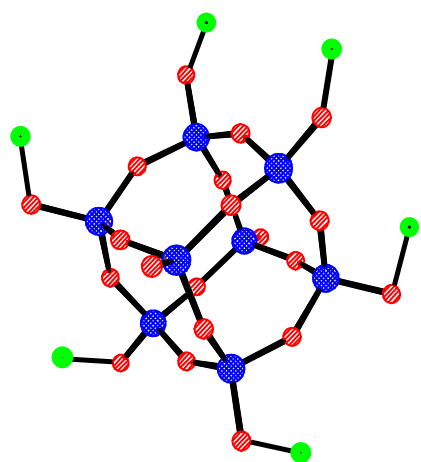
Charles Vriamont, Michel Devillers, Olivier Riant,* and Sophie Hermans*^[a]

have shown that recycling is possible at low temperatures. To the best of our knowledge, this is the first example of a supported gold catalyst on carbon nanotubes, either by covalent or non-covalent functionalisation, and the approach could open the door to further applications.

Single site catalysts

- What is it?
 - **Individual isolated ion/atom/molecular complex/cluster**
 - Grafted on porous support
 - **Created within the material by building block approach**
 - „Ship in bottle“ structures– e.g. molecular complex/enzyme trapped within a zeolitic cage
 - Crystalline, open-structure, microporous solids (e.g. zeolites) with active sites uniformly distributed throughout the bulk

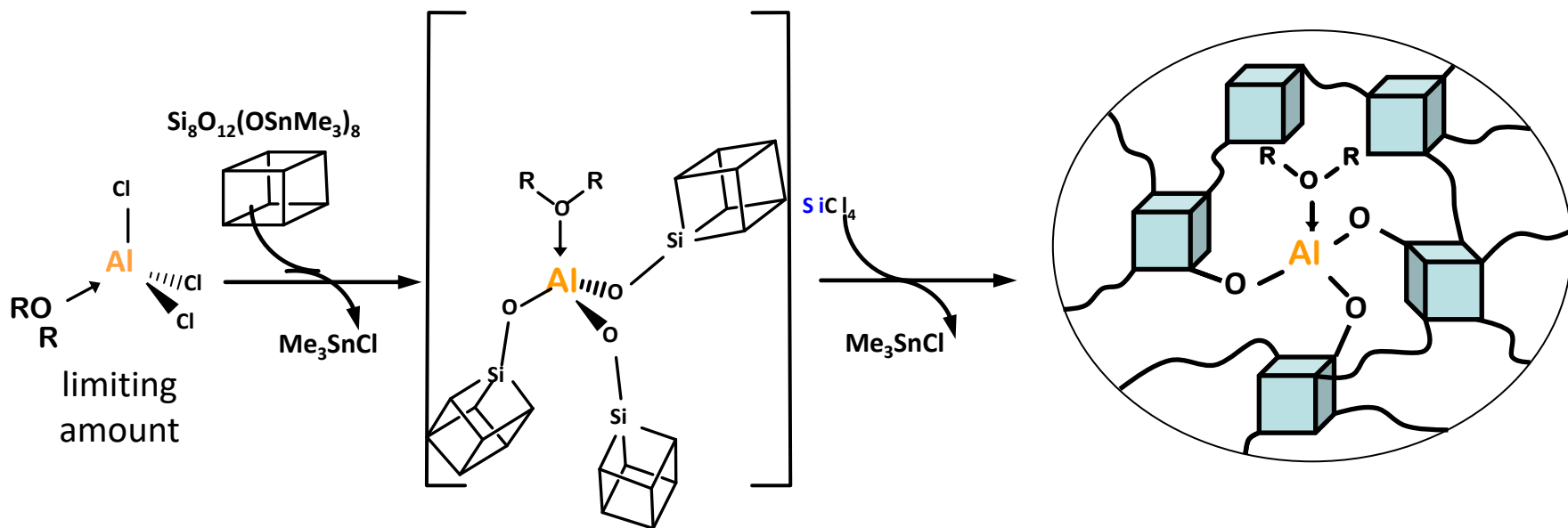
Single site catalysts



1. N.N. Ghosh, J.C. Clark, G.T. Eldridge, C.E. Barnes, Chem. Comm., (2004) 856-857.

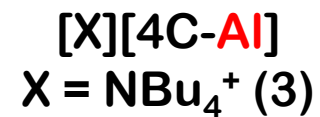
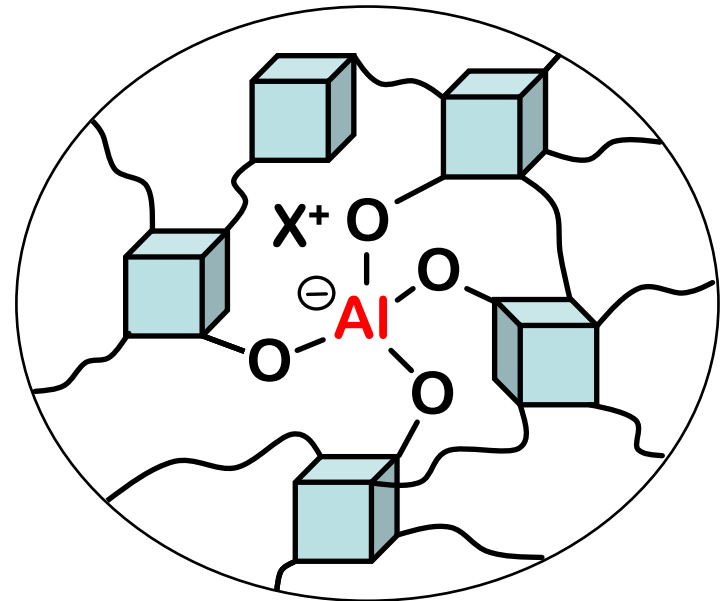
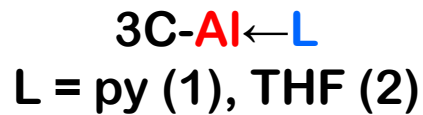
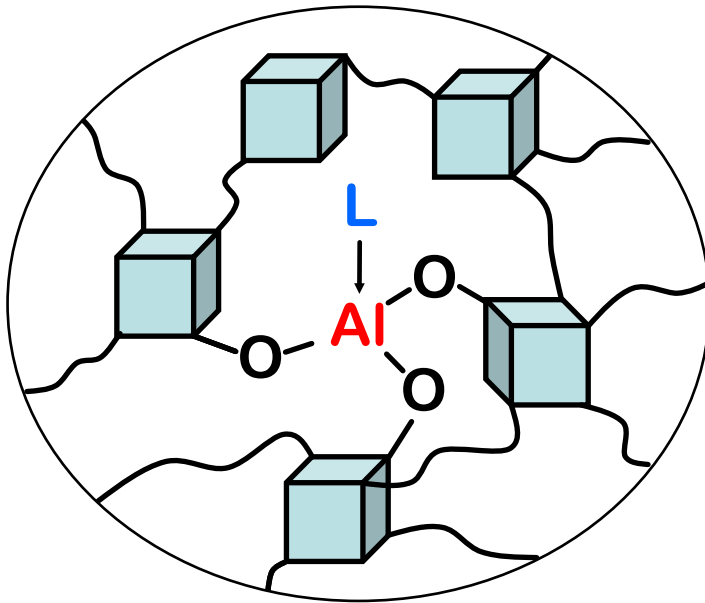
2. M.-Y. Lee, J. Jiao, R. Mayes, E. Hagaman, C.E. Barnes, Catalysis Today, 160 (2011) 153-164.

Single site catalysts



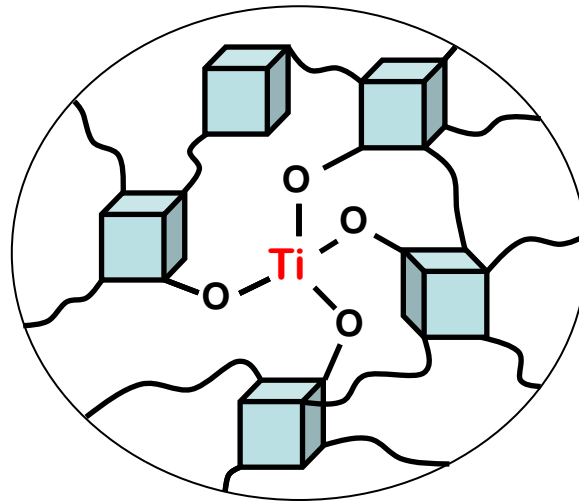
Single site catalysts

- Targeting connectivity




Single site catalysts

- Targeting geometry
 - Tetrahedral
 - Square planar



4C-Ti

Single site catalysts

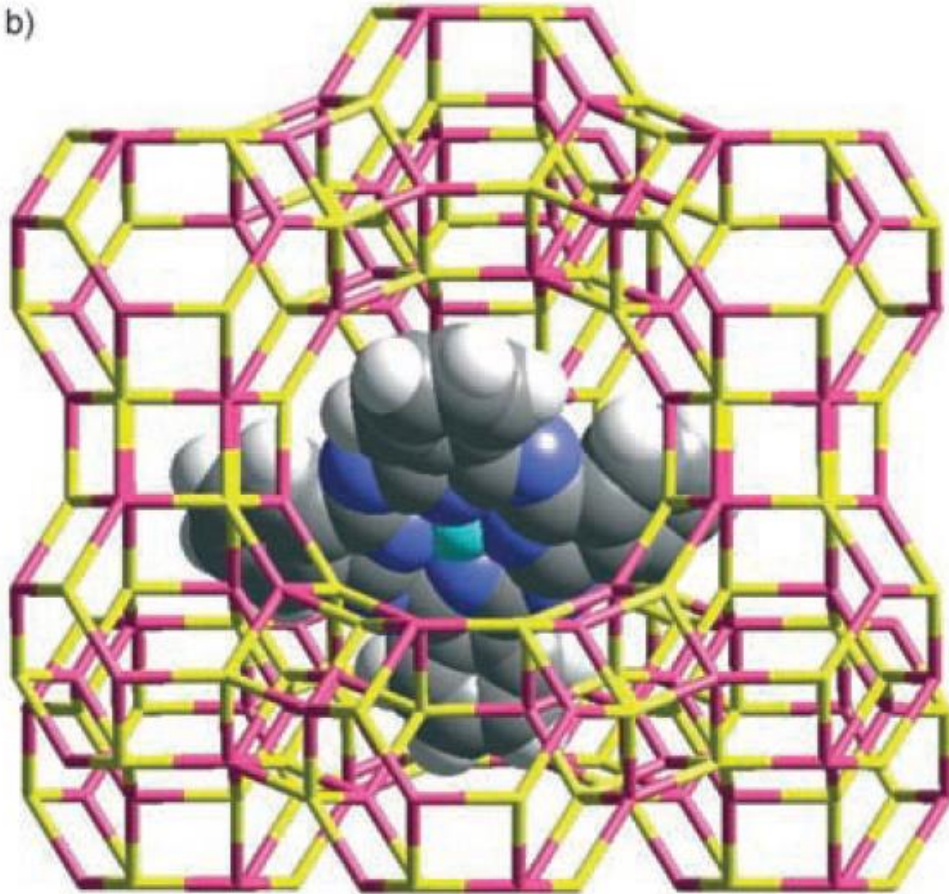
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 - „Ship in bottle“ structures– e.g. molecular complex/enzyme trapped within a zeolitic cage
 - Crystalline, open-structure, microporous solids (e.g. zeolites) with active sites uniformly distributed throughout the bulk
- CHARACTERIZATION?
- 

Single site catalysts

- What is it?
 - Individual isolated ion/atom/molecular complex/cluster
 - Grafted on porous support
 - Created within the material by building block approach
 - **„Ship in bottle“ structures– e.g. molecular complex/enzyme trapped within a zeolitic cage**
 - Crystalline, open-structure, microporous solids (e.g. zeolites) with active sites uniformly distributed throughout the bulk

Single site catalysts

b)



Cobalt phthalocyanine within zeolite Y

Single site catalysts

- Single site very well preserved (no dimerization,...)
- Diffusion of molecules small enough in the micropore system of zeolite – both reactants and products – enhancing specificity and selectivity

Single site catalysts

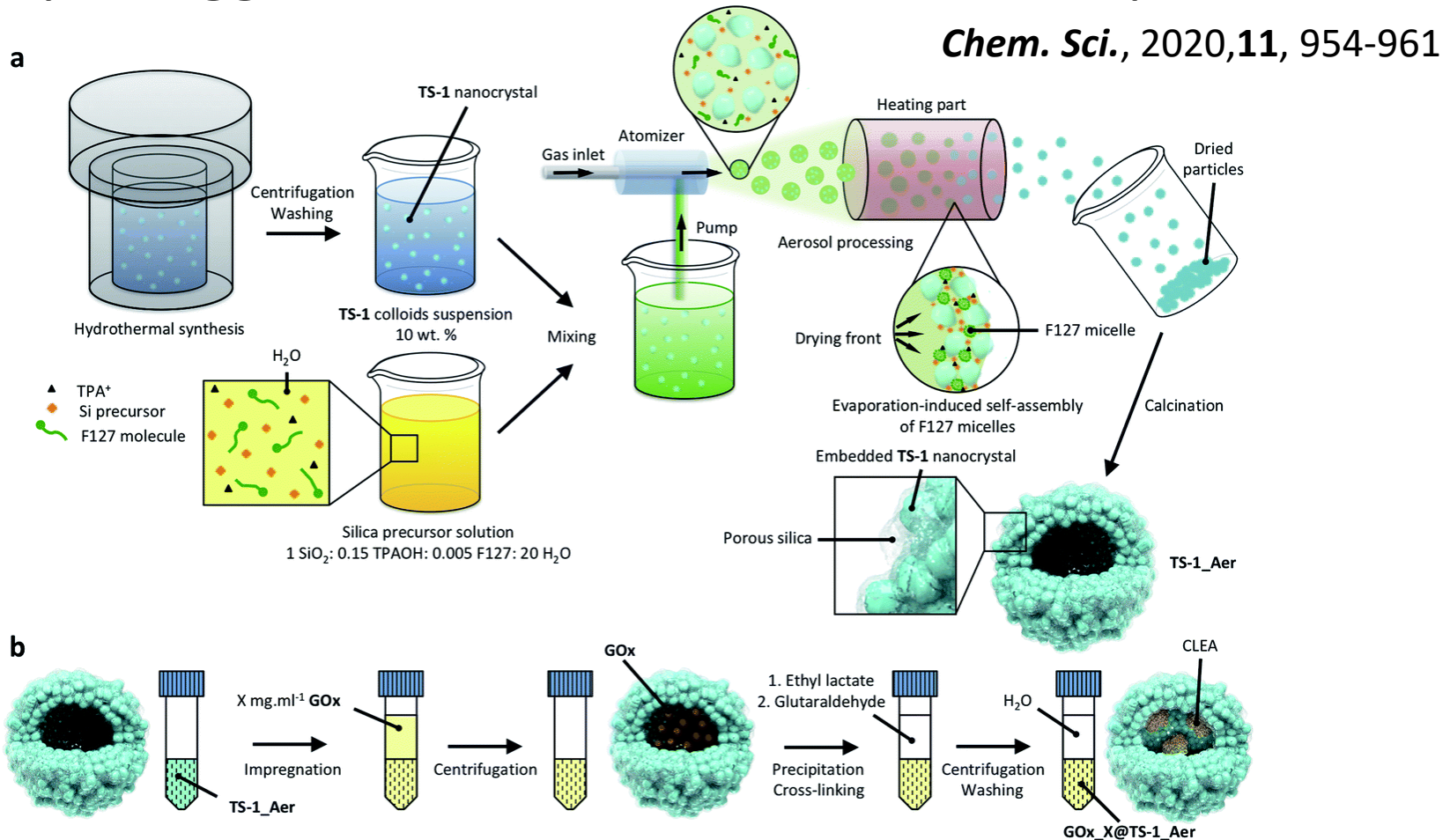
- Synthesis?
 - Cation exchange (2Na^+ for Co^{2+})
 - Complexation with ligands within the zeolite pores

„ Co^{2+} -exchanged zeolite-Y was heated with excess amount of 1,2-dicyanobenzene (DCB) under vacuum. Excessive DCB was then extracted (Soxhlet).

The dicyanobenzene molecule is small enough ($\sim 6.5 \text{ \AA}$) to diffuse through the 7.4 \AA windows of the supercage of the zeolite and condense around the metal ion to form cobalt phthalocyanine.“

Single site catalysts

- Enzyme agglomerates inside a hollow silica sphere



Single site catalysts

- What is it?
 - Individual isolated ion/atom/molecular complex/cluster
 - Grafted on porous support
 - Created within the material by building block approach
 - „Ship in bottle“ structures– e.g. molecular complex/enzyme trapped within a zeolitic cage
 - **Crystalline, open-structure, microporous solids (e.g. zeolites) with active sites uniformly distributed throughout the bulk**

Single site catalysts

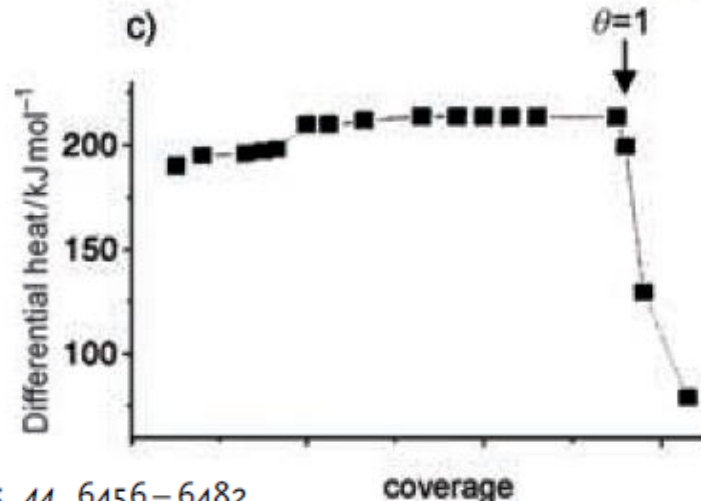
- Zeolites
 - $\equiv\text{Si}-\text{O}(\text{H})-\text{Al}\equiv$
- MAIPOs
 - $\equiv\text{M}^{\text{II}}-\text{O}(\text{H})-\text{P}\equiv$
 - M = Mg, Co, Zn, Mn...

Single site catalysts

- Zeolites and MAIPOs
 - Microporous
 - Crystalline
 - Ideal to study by many analytical techniques

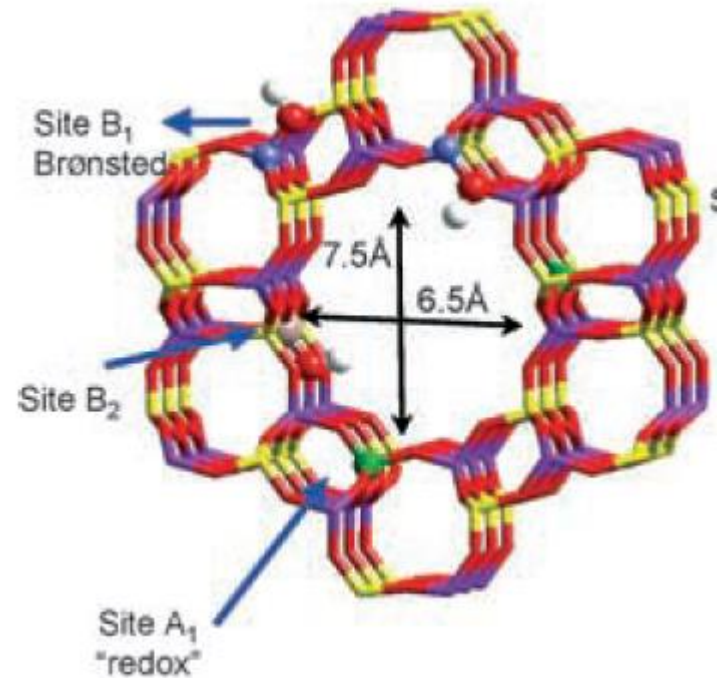
Single site catalysts

- Zeolites and MAIPOs
 - Isolated sites???
 - Si/Al ratio ≥ 200 ; perfect crystallinity
 - Equivalent sites???
 - Amorphous grains/surface species



Single site catalysts

- Zeolites and MAIPOs
 - Isolated sites???
 - Equivalent sites???
 - Different positions in cage
 - Amorphous grains/surface species



Single site catalysts

- Zeolites and MAIPOs
 - Isolated sites???
 - Equivalent sites???
 - Amorphous grains/surface species
 - e.g. extraframework aluminum species
 - From not fully embedded (connectivity = 3) surface Al atoms to amorphous alumina (nano)particles
 - **Tetra**, penta, hexacoordinated
 - Easy to overlook (99 % of the material is crystalline), but important to notice
 - Their role in catalysis???

Single site catalysts

- Similar but different (Markus Antoinetti et al.)

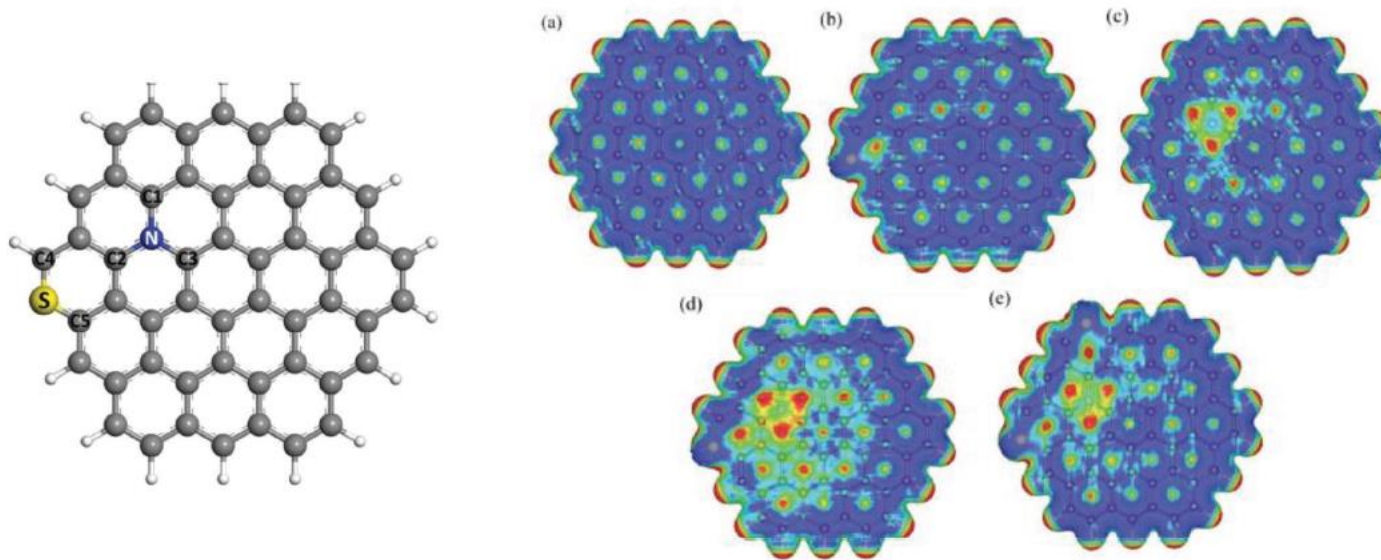


Figure 7. Molecular model of S,N dual-doped graphene and electrostatic potential mapping from charge density matrix for: a) nondoped model graphene, b) S-G, c) N-G, d) S-N-G, and e) S-S-N-G. Reproduced with permission.^[117] Copyright 2015, Wiley-VCH.

- Doped graphene sheets
- Isolated sites located by HR-TEM

Single site catalysts

- Doped graphene sheets
 - Single **metal** atoms within carbon layer
 - Single atom = „complex like“
 - Conductive carbon layer, electrons shared = „metal like“
 - **Unique**
 - Single-site Au highly active in Haber-Bosch ammonia synthesis, mild conditions

COMMUNICATION

N₂ Fixation

Single-Site Gold Catalysts on Hierarchical N-Doped Porous Noble Carbon for Enhanced Electrochemical Reduction of Nitrogen

*Qing Qin, Tobias Heil, Markus Antonietti, and Martin Oschatz**



Single site catalysts

- Doped graphene sheets
 - Single **Au** atoms within N-doped graphene

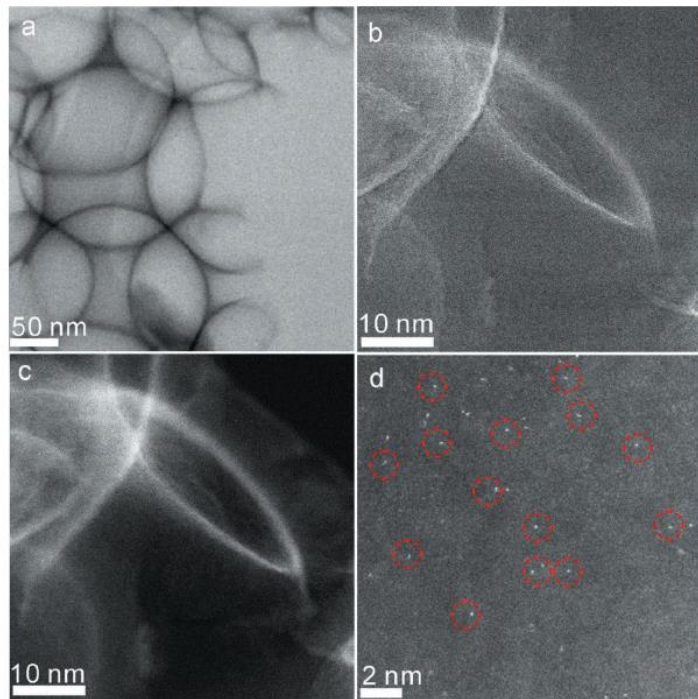
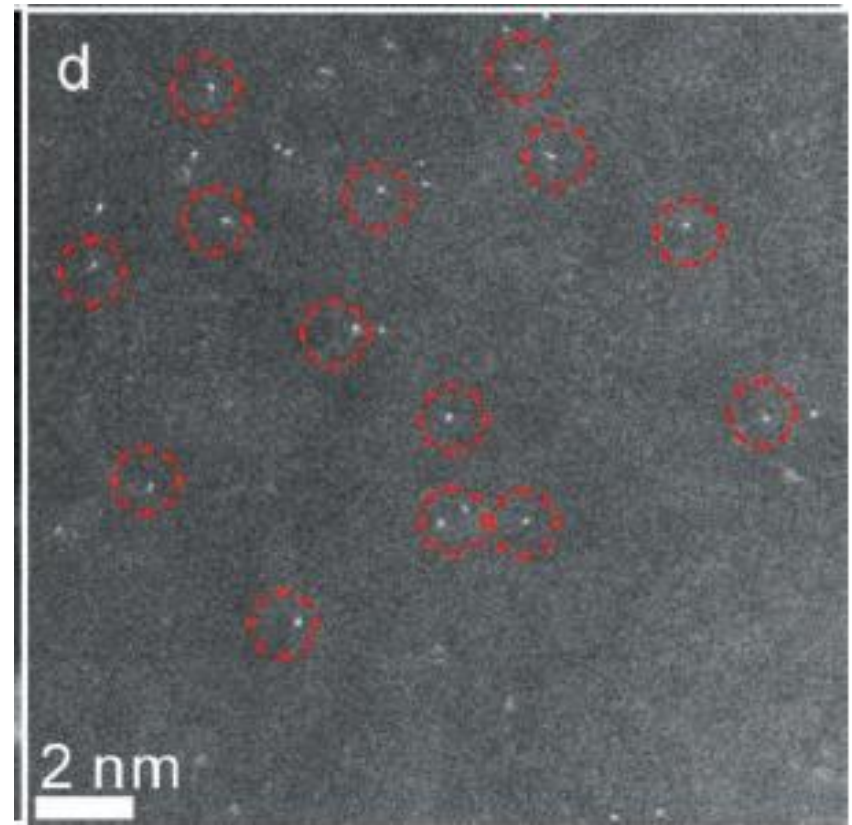


Figure 1. a) Representative TEM image of AuSAs-NDPCs. b) Aberration-corrected STEM image in bright-field mode. c) Aberration-corrected STEM image in dark-field mode. d) High-magnification HAADF-STEM image, showing that only Au single species is present.



References

Reviews

J. M. Thomas et al.

Heterogeneous Catalysts

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Single-Site Heterogeneous Catalysts**

John Meurig Thomas, Robert Raja, and Dewi W. Lewis*

The concept, reality and utility of single-site heterogeneous catalysts (SSHCs)†

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