Sonoluminescence

After thermal annealing at 350°C.

Growth & Implosive Collapse of Bubbles

Sonochemistry & Materials

Maria Fortunato, Jinrui Guo, Maryam Sayyah, Hangxun Xu, Brad Zieger

Hollow Spheres and Crystals

Bi2O3, As prepared initially. After thermal annealing at 50°C. 1st Hollow Crystals!

Fluorescent Carbon Nanodots

Bubbles collapse near surfaces create high-velocity jet-microscopic depth charge.

Near Surfaces and Interparticle Collisions

We ask people hand together due to shock waves from imploding bubbles.

Fluorescent carbon nanodots made by co-axial Hollow Reaction of carbon nanoparticles.

Sonoluminescence

Mechanoluminescence from Acoustic Cavitation

Mechanical Stress → Light

Suslick Group

Sonochemistry & Materials Chemistry

Ultrasonic Spray Pyrolysis, Nanomaterials

Sonoluminescence

Olfaction and Molecular Recognition

The Optoelectronic Nose

www.scs.uiuc.edu/suslick

Ultrasonic Spray Pyrolysis (USP)

Continuous Production of Nano-Materials

New Synthetic Methods for Nanomaterials

Maria Fortunato, Brandon Ito, Howard Kim, John Overcash, Maryam Sayyah

Olfaction & the Optoelectronic Nose

Jon Askim, Minseok Jang, Wei Jiang, Jonathan Kemling, Hengwei Lin

Chemo-Responsive Nanoporous Pigments:

Metall-Ligand Dyes: Lightemitting indicators

Precursor

Characteristic wavelengths (nm)

Metal ion dyes

Extended π-Systems

Phosphines

Acids

Aldehydes

Amines

Hydrocarbons

Carboxylic

Amides

Thioethers

Phosphites

Thiazoles

Ethers

Esters

Alcohols

Ketones

Trifluoromethanes

Nitriles

Silanes

Acids

Phosphate
drus

Sonochemical Synthesis of Amorphous Nanoparticles

- Solution of Fe(CO)5 in 1-hexanol, under Ar, with ethyl acetate. 20°C, 20 kPa, 80 W
- Amorphous on nm scale: XRD, DSC, e-beam Microdiffraction
- Superparamagnetic (i.e., single domain ferromagnet)
- High Magnetization comparable to commercial ferrioxides

Fluorescent Carbon Nanodots

Quantum Dots

Nano-Catalysts

Solvent

Precursor

Metal

Metal Salts

Aliphatic

Ammonia

Arsine

Acids

Amines

Aldehydes

Phosphines

Tri-n-Bu

Zinc Phosphide

Diisobutylamine

Pyridine

2-Picoline

3-Picoline

3,4-Lutidine

aniline

DiMePh

Phosphine

Identification of chemical classes, even for unknown odorants

The Chemist’s “Radiation Badge” for Toxic Gases

ΔR, G, B). All VOCs easily distinguished. The Chemist’s “Radiation Badge” for Toxic Gases

Δ

H2S

HF

HCN

Cyclohexanethiol

Benzylthiol

3-Heptonone

3-Decanone

2-Octanone

Ethyl benzoate

Methylic Acids

1-Pentanethiol

1-Hexanethiol

1-Octanethiol

Cyclopentanol

Ammonia

Nitric acid

Benzenetoluenep-xylene

1-Decanol

Nonanol

Heptanol

Cycloheptanol

Benzalcohol

Unknown odorants!

Cutaneous receptors speculative, but probably metalloproteins with conserved tripeptide.

Receptor structure speculative, but probably metalloproteins with conserved tripeptide.

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Δ
Suslick Group Overview
University of Illinois at Urbana-Champaign
www.scs.uiuc.edu/suslick ksuslick@uiuc.edu

Sonochemistry: Nanomaterials from Ultrasound
High Intensity Ultrasound and Ultrasonic Spray Pyrolysis


Sonoluminescence


Chemical Sensing

I. Sensors and Chemical Sensing

Mechanisms of Molecular Recognition
Chemical Sensing & Chemical Sensors: “Smell-Seeing”
Biophysics of Smell and Taste

II. Chemical Effects of Ultrasound

Sonoluminescence and Spectroscopy
Synthetic Applications of Sonochemistry
Nano-Materials and Catalytic Applications

FRENAQs™

Frequently Not-Asked Questions: Educational Philosophy

• Undergraduate education is the learning of that which is already known:
  Graduate education is the learning of that which no one knows.

• Graduate education is learning how to do what we call research: i.e.,
  Graduate education is learning how to learn the unknown.

• I expect my students to become independent researchers: I cannot do that if I treat you like a technician!
Criteria: The very best research permanently changes the way people think about some field of knowledge. If the goal of a project doesn’t ultimately come up to that standard, the result will be boring.

Pure vs. Applied: Pointless distinction. More important: Is it interesting or boring?

Interdisciplinary and Multidisciplinary: Both between areas of chemistry and including elements from multiple fields of science.

Chemistry: 1900

Analytical  Inorganic
Physical    Organic
“Forward, in all directions!” – Leon Trotsky
Chem-Space

Living

Biochemistry

BioPhysical

Polymeric Materials

Inorganic Materials

Materials Engineering; Solid State Physics

Non-Living

Nuclear Physics

Inorganic

Organo-metallic

Physical

Large

Small

1 amu 10 100 1000

10^5 10^6 10^7

Research in the Suslick Group

Living

Protein Microspheres

Nanoporous Pigments: Sol-Gel Sensors

Sonochemical Synthesis of Nanostructured Materials

Non-Living

Chemical Sensing

Sono-luminescence

Small

1 amu 10 100

Large

10^7

10^8 10^7

10^6 10^5

10^4 10^3 10^2 10^{1.5}
# Current Group GSs & PDs (10/2011)

## Sensors
- **Jon Askim**  
  B.S., Western Washington Univ., 2008.  
- **Minseok Jang**  
  B.S., Harvey Mudd, 2006.  
- **Hengwei Lin (PDRA)**  
  P.D., Stanford Univ.  

## Sonochemistry
- **Ginruo Guo**  
  B.S., Nanjing Univ., 2009.  
- **Howard Kim**  
- **John Overcash**  
- **Darya Radziuk (PDRA)**  
  Ph.D. Max-Planck Inst., 2010.  
- **Maryam Sayyah**  
- **Sizhu You**  
- **Brad Zieger**  
  B.S., Western Washington Univ., 2007.  

## Group Admin.
- **Nasrin Gahvari**

---

# Past Group Members (2001-2011)

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/Position</th>
<th>Company/Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gennady Dantsin</td>
<td>B.S., S.U.N.Y., Binghamton.</td>
<td>Dekka Batteries</td>
</tr>
<tr>
<td>Nate Eddingsaas</td>
<td>B.S. U. Wisc.</td>
<td>Postdoc, Caltech (Okimura)</td>
</tr>
<tr>
<td>Ming Fang</td>
<td>B.S. Jiin U.</td>
<td>PNNL</td>
</tr>
<tr>
<td>Dave Flannigan</td>
<td>B.S., U. Minn.</td>
<td>Postdoc, Caltech (Zewail)</td>
</tr>
<tr>
<td>Maria Fortunato</td>
<td>B.S., Penn State</td>
<td>Intel</td>
</tr>
<tr>
<td>Richard Helming</td>
<td>B.S. U. Florida</td>
<td>Mine Safety &amp; Health Admin.</td>
</tr>
<tr>
<td>Steve Hopkins</td>
<td>B.S., Washington &amp; Lee</td>
<td>Intel</td>
</tr>
<tr>
<td>Wei Jiang (PDRA)</td>
<td>Ph.D., UNM, 2009.</td>
<td>Postdoc, Stanford (Cool)</td>
</tr>
<tr>
<td>Jonathan Kemling</td>
<td>B.S., Michigan Tech.</td>
<td>3M</td>
</tr>
<tr>
<td>Margaret Kosal</td>
<td>B.S., USC.</td>
<td>Asst. Prof., Georgia Tech</td>
</tr>
<tr>
<td>Tanya Prozorov</td>
<td>M.S., Bar Ilan U.</td>
<td>DOE Ames Lab</td>
</tr>
<tr>
<td>Jennifer Ponder</td>
<td>B.S., Ball State.</td>
<td>Colgate-Palmolive</td>
</tr>
<tr>
<td>Neil Rakow</td>
<td>B.S., Colorado School of Mines.</td>
<td>3M</td>
</tr>
<tr>
<td>Sara Skrabalak</td>
<td>B.S., Washington U.</td>
<td>Asst. Prof., Indiana Univ.</td>
</tr>
<tr>
<td>Won Suh B.S.</td>
<td>Seoul National.</td>
<td>Postdoc, UCB (Tirrell)</td>
</tr>
<tr>
<td>Farah Toublan</td>
<td>B.S., SUNY Buffalo</td>
<td>Stepan Chemicals</td>
</tr>
<tr>
<td>Jiangyun Wang</td>
<td>B.S., USTC.</td>
<td>Prof., Beijing Inst. Biophysics</td>
</tr>
<tr>
<td>Hangxun Xu</td>
<td>B.S., USTC, 2006</td>
<td>Postdoc, UIUC (Rogers)</td>
</tr>
<tr>
<td>Chris Ziegler</td>
<td>B.S., Bowdoin College</td>
<td>Assoc. Prof., Univ. of Akron</td>
</tr>
</tbody>
</table>
### Current Research Funding (09/2011)

2011 – 13  
DoD; “An Optoelectronic Nose for Detection of Improvised Explosives”  
$712,000 / yr.  $1,450,000 total.

2011 – 15  
ONR; “Spontaneous energy concentration in energetic molecules, Interfaces and composites.”  
Collaboration w/ D. Dlott; $400,000 / yr.  $1,200,000 total.

2007 – 11  
NIH; “Colorimetric Sensor Arrays for VOC Dosimetry”  
$600,000 / yr.  $2,460,000 total.

2010 – 13  
NSF CHE; “Chemical Effects of High Intensity Ultrasound: Sonoluminescence”  
$140,000 / yr.  $420,000 total.

2009 – 11  
NSF DMR; “New Sonochemical Methodologies for Nanostructured Materials,”  
$190,000 / yr.  $280,000 total.

2010 – 12  
EBI; “Applications of Ultrasound to Biofuel Production”  
$120,600 / yr.  $241,000 total.

**Total Recent Funding:**  $6.1 M

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### Group Meetings

**USUAL MEETING TIME:**  
Mondays, 10:00 a.m., A414 CLSL.  
[www.scs.uiuc.edu/suslick/groupmeetings](http://www.scs.uiuc.edu/suslick/groupmeetings)

**SMALL GROUP MEETINGS**  
Informal gatherings to discuss research results, problems and ideas.

**INDIVIDUAL MEETINGS**  
Candid evaluation of progress and goals.  
1-2 page typed summary with attached critical data

**RESEARCH TALKS**  
About 40 minutes long, semi-formal with handout.

**LITERATURE TALKS**  
Review 3-4 recent papers from a single author or on a single topic.  
A brief handout for group.
I. Sensors and Sensing

Mechanisms of Molecular Recognition
Chemical Sensing & Chemical Sensors: “Smell-Seeing”
Biophysics of Smell and Taste

II. Chemical Effects of Ultrasound

Sonoluminescence and Spectroscopy
Synthetic Applications of Sonochemistry
Materials and Catalytic Applications
New Materials for Solar Energy Conversion
The Mammalian Olfactory System

- Olfactory epithelium
  - human: 1 cm² per nostril ($5 \times 10^7$ cells)
  - dog: ~25 cm² per nostril, highly reticulated
- Even Humans can distinguish >10,000 individual scents.
- ~500 semi-specific receptors: 2% of mammalian genome!
- Receptor structure speculative, but probably metalloprotein
  Wang, Luthey-Schulten, Suslick, PNAS 2003, 100, 3035.

Chemical Sensing

**Need:** Low-cost, but sensitive analysis of molecules in air.

**Uses:**
- Non-invasive Medical diagnosis
- Chemical spills and toxins
- Security screening
- Personal Hygiene
- Food and drug spoilage
- Process control ...

**Problem:** Current Technology is not sensitive, not portable, or not cheap.
How do molecules recognize each other?

**Intermolecular Interactions:**
- Lewis (e⁻ pair) Donor – Acceptor
- Brønsted (proton) Acid – Base
- ‘Charge-Transfer’, π–π Complexes
- Hydrogen Bonding
- Dipole – Dipole
- van der Waals (physisorption)

Most chemical sensing technology relies on the **weakest and least selective interactions!**

---

**Sensor Arrays: Concepts**

- Make sensors **disposable**.
- Probe a **wide** range of chemical interactions, **including strong** sensor-analyte interactions.
- But still **equilibrium** based: dose independent & reversible.
- Biomimetic: **array of semi-specific sensors**.
- Include **metal ion** containing (Lewis acid) sensors (as with the olfactory receptors, more later).
- **Do it cheap**: use **visual** reporters. Convert olfactory-like responses to a visual output.
Nanoporous Pigment Sensor Arrays

Chemo-responsive Pigment Classes:
- **Lewis Acid Dyes**: metal ion containing dyes
- **Brønsted Acid/Base Dyes**: pH indicators
- **Dyes with Large Dipoles**: solvatochromic
- **π-Complexing Dyes**: extended π-π* dyes

Universal standard sensor array for sensing of all VOCs.

Colorimetric Array Detector

- Printed array of *chemically responsive* dyes.
- Digitally image before & after exposure & subtract.
- Difference Map is a “molecular fingerprint”:
  a unique 108-dimensional vector (36 ΔR, ΔG, ΔB).
**Difference Maps are Molecular Fingerprints**

- decylamine
- sec-Bu$_2$amine
- aniline
- 2-picoline
- acetic acid
- hexanethiol
- benzylthiol
- ethanol
- pentanol
- CF$_3$CO$_2$H
- PhMe$_2$phospine
- Bu$_3$phosphine
- hexanal
- benaldehyde
- 1-octene

Every volatile organic has a unique pattern, but with familial resemblances!

---

**Hierarchical Cluster Analysis**

- Distance on x-axis gives “dissimilarity” (i.e., cluster radius).
- Connectivity is meaningful, not vertical position.
- Centroids of clusters are used for further clustering.
- Dendrogram quantitatively shows what resembles what.
12

HCA of 100 VOCs: All Distinct and Identifiable

Identification of chemical classes, even for unknown odorants!

Squared Euclidean (Minimum Variance)

20 High Hazard TICs at IDLH + DNT

Every pattern unique. In septuplicate trials (n=147), no statistical confusions at IDLH.
• **Diagnosis of infections still relies on cell culturing.**
  
  ~$10^6$ bacteria for visible colony;
  
  ~24 to 48 hrs for many, BUT >7 days for others (e.g., TB).

• **Bacteria better monitored by VOCs:**
  
  Volatiles in closed container are an integral of growth.

• **Can we differentiate bacteria by smell?**

- Array in Petri Dish
- Inoculant: 200 µl BHI liquid at 1 O.D.
- Solid Medium: TSA w/ 5% sheep blood
Human pathogenic bacteria clearly differentiable.

**Pathogenic Bacteria**

<table>
<thead>
<tr>
<th>Bacteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. aureus</td>
</tr>
<tr>
<td>S. aureus MRSA</td>
</tr>
<tr>
<td>S. sciuri</td>
</tr>
<tr>
<td>S. epidermidis</td>
</tr>
<tr>
<td>E. faecium</td>
</tr>
<tr>
<td>P. aeruginosa</td>
</tr>
<tr>
<td>E. faecalis VRE</td>
</tr>
<tr>
<td>E. faecalis</td>
</tr>
<tr>
<td>E. coli 53502</td>
</tr>
<tr>
<td>E. coli 25922</td>
</tr>
</tbody>
</table>

**Pathogenic Bacterial Growth Curves**

Human pathogenic bacteria rapidly differentiable (~3 hr).

20 most responsive ΔRGBs vs. time (agar plate; TSA + 5% sheep blood)
**Hand-held Colorimetric Reader Prototype**

- **PC on a chip:** Toradex Colibri PXA320; 0.8 GHz, 1GB, USB, WiFi, GPS.
- **Touchscreen:** Sharp WQVGA TFT
- **4” (next version: <3” x 6”)**
- **Sheaths/Inlet:** disposable sensor array
- **Parker Micro-pump**
- **Micron CMOS camera (white LED below)**
- **4 AA or Rechargeable Li batteries**

---

**Next Gen.: Linear Sensor Array with CCIS**

- **A8 sized CCIS:** 72 x 18 x 12 mm  
  2 7/8” x  ¾” x  ½”
- **Color Contact Image Sensor (CCIS):** digital copiers and card scanners.
- **300 dpi CMOS linear image sensor.**
- **Very low power consumption.**
- **Analog output from photodiode.**
- **1V 12 bit A/D improves S/N by ~32-fold vs. usual 8 bit CMOS camera or scanner.**
- **Requires linear colorimetric array:** better gas flow, lower dead volume, faster response time.
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Cavitational Collapse of Single Bubble

Strobed Single Bubble

\[ R_{\text{max}} \sim 50 \ \mu\text{m} \]
\[ R_{\text{min}} < 1 \ \mu\text{m} \]
35 kHz
MBSL from Cr(CO)$_6$ in Hexadecane

Temperature vs. Calculated Cr Spectra

- Cr: 4700 K ± 300 K
- Mo: 4800 K ± 400 K
- C$_2$: 4900 K ± 300 K
- Fe: 5100 K ± 350 K
Why Nanostructured Catalysts?

• Nanostructured: 1-10 nm, 100 to $10^4$ atoms.
• Properties distinct from either bulk or molecular.
• Surface atoms predominate: surface highly defected.
• High catalytic activity, often unusual selectivities.

Why Sonochemistry?

• Unique interaction of energy and matter.
• Every bubble is an isolated $10^{-18}$ L (aL) reactor.
• Extreme conditions, but extraordinary quench rates.
• Easy to produce both in lab and in scale-up.

Sonochemical Synthesis of Nanostructured Materials
Sonochemical Synthesis of Amorphous Iron Colloid

Sonication of Fe(CO)$_5$ in 1-hexanol, under Ar, with oleic acid or polyvinylpyrrolidone, 20°C, 20 KHz, 80 W

Amorphous on nm scale: XRD, DSC, e-beam Microdiffraction

Superparamagnetic (i.e., single domain ferromagnet)

High Magnetization comparable to commercial ferrofluids

Heterogeneous Catalysis with Nanostructured Materials

Goals:

Stable High Surface Energy Materials (i.e., highly defected surfaces)

Refractory Materials with High Surface Areas

Catalytic Reactions of Use:
Hydrodesulfurization (HDS)
Hydrodehalogenation (HDH)
**Hollow MoS₂**

TEM hollow MoS₂ nanospheres after thermal annealing at 450°C.

1. Sonicate \( \text{Mo(CO)}_6 + S_8 + 100\text{nm SiO}_2 \rightarrow \text{MoS}_2 \text{ on SiO}_2 \)
2. HF wash to remove SiO₂ core.

---

**Hollow Crystals (!) of MoO₃**

As prepared initially. After thermal annealing at 350°C.
**MoS$_2$ Nanospheres: HDS of Thiophene**

After 24 hours of catalysis.

![Graph showing activity of MoS$_2$ catalysts at different temperatures.](image)

**Sonocrystallization of Aspirin**

![Images showing sonocrystallization process.](images)
## Comparison of Preparation Methods

Aspirin crystallized from acetic acid at 20 °C

<table>
<thead>
<tr>
<th>Method</th>
<th>As-Received</th>
<th>Stirred</th>
<th>Seeded</th>
<th>Hand-Ground</th>
<th>Sonocrystallized: Cleaning Bath</th>
<th>Sonocrystallized: Horn Immersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Received</td>
<td>100 μm</td>
<td>25 μm</td>
<td>25 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Stirred</td>
<td>100 μm</td>
<td>25 μm</td>
<td>25 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Seeded</td>
<td>100 μm</td>
<td>25 μm</td>
<td>25 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Hand-Ground</td>
<td>100 μm</td>
<td>25 μm</td>
<td>25 μm</td>
<td>100 μm</td>
<td>100 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Sonocrystallized:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning Bath</td>
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<td></td>
</tr>
<tr>
<td>Horn Immersion</td>
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</tbody>
</table>

Horn sonocrystallized aspirin exhibits less clumping and has an excellent size distribution. (Ultrasonic bath ineffective, as expected.)

## Sonofragmentation: Time & Intensity

<table>
<thead>
<tr>
<th>Aspirin, initial</th>
<th>5.5 W 1 minute</th>
<th>10 W 1 minute</th>
<th>30 W 1 minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspirin, initial</td>
<td>25 μm</td>
<td>25 μm</td>
<td>25 μm</td>
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</tbody>
</table>

### Graphs

- **Graph 1**: Average Volume per Particle (μm³) vs. Acoustic Intensity (W)
- **Graph 2**: Average Volume per Particle (μm³) vs. Time (min)

- **Graph 1**: Data points for 10 W and 30 W are plotted.
- **Graph 2**: Data points for 10 W and 30 W are plotted.
Low Aspect ratio crystal morphology expected for friable materials:
Needles will be broken in half above some threshold length.

Various possible breakage mechanisms:
- Particle-horn collisions
- Particle-cell collisions
- Particle-particle collisions
- Particle-shockwave interactions

Effect of Particle Loading
Sonicated at 5.5 W for 10 seconds

No particle concentration dependence is observed (!) Therefore, mech. must be direct shockwave fragmentation, not interparticle collisions.
**Ultrasonic Fountain and Nebulization**

Ultrasonic Spray Flow Synthesis

**Synthetic Methodology:**

- **Easy nanoparticle synthesis:** droplets as isolated femtoliter reactors.
- **One pot encapsulation, polymerization, & drying:** in situ template synthesis.
- **Porous solid synthesis:** matrix with pyrolyzable template.
- **Continuous and large scale production possible.**

**USP is an easily scalable & versatile synthetic methodology.**
USP of CdSe Q-dots

Conditions: Cd Ac₂, Stearic acid, TOPSe
residence time ~2 s.

USP Synthesis of Porous MoS₂

8:1 mole ratio Snowtex 80 nm colloidal silica to (NH₄)₂MoS₄
Excess 10% HF in EtOH 100 m²/g

4:1 mole ratio Ludox 20 nm colloidal silica to (NH₄)₂MoS₄
Excess 10% HF in EtOH 250 m²/g

Silica-MoS₂ Composite

Porous MoS₂

Leaching of SiO₂ yields high surface area, porous MoS₂
USP Porous Carbons

- New, facile route to porous carbons
- *In situ* template generation & removal
- Potential catalytic, adsorbent, and electrochemical applications
- Easy scale-up

Sucrose-Based Porous Carbon via USP

- Scalable production technology: USP
- Simple, cheap precursors: sugar, carbohydrates.

\[
C_n(H_2O)_n \rightarrow n\ C + n\ H_2O\uparrow
\]

- No hazardous decomposition byproducts.
- Rational design of very high surface area carbons.
- Addition of alkali carbonate or nitrate salt to precursor promotes decomposition of sucrose and gas decomposition products create internal pores.
**Internal Porosity vs. Salt**

USP 0.5 M Sucrose + Salt, 800 °C, 1 L/min Argon

<table>
<thead>
<tr>
<th>Solution</th>
<th>Surface Area (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 M NaNO₃ solid</td>
<td></td>
</tr>
<tr>
<td>0.5 M Na₂CO₃</td>
<td>S. A. ~ 440 m²/g</td>
</tr>
<tr>
<td>0.5 M NaHCO₃</td>
<td>S. A. ~ 800 m²/g</td>
</tr>
<tr>
<td>1.0 M Na₂CO₃</td>
<td>S. A. ~ 1115 m²/g</td>
</tr>
</tbody>
</table>

**Characterization of Porosity**

TEM and BET shows hierarchical pore structure.

High surface areas indicate microporous shell allows access to internal macropores.

Very narrow micropore distribution at 0.6 nm
Conclusions

• Ultrasound does High Energy Chemistry thru Cavitation.
  Cavitation Clouds:  5000 K, ~300 Atm., ~10^{-9} sec.
  Single Bubbles:  >15,000K, ~1100 Atm., <10^{-9} sec.

• Sonochemistry: new tool for nanophased materials.
  Metals, alloys, carbides, sulfides, oxides all available:
  as colloids, supported catalysts, nanoporous solids.

• Extremely Active New Nanostructured Catalysts.

• Heterogeneous Systems: diverse & dramatic enhancements

• Metal Surface Activation: Inter-Particle Collisions.

• Ultrasonic Spray Pyrolysis as a versatile synthetic route.