X-ray Imaging and Spectroscopy of Individual Nanoparticles

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D \sim 8 \text{ nm}
Magnetism in reduced dimensions

- Intrinsic properties
- Interparticle interactions
- Finite-size effects
- Size, aspect ratio distribution
- Surface effects

Nanomagnetism
Magnetism in reduced dimensions

Superparamagnetism

Shape-dependent Thermal Switching
Superparamagnetic Nanoislands

Superparamagnetic limit: time and thermal stability

\[ K_{ani} \cdot V_{\text{particle}} \approx k_B \cdot T \]

Magnetism in reduced dimensions

Surface and core magnetic orders
- high-field irreversibilities
- high saturation fields
- shifted hysteresis loops

Surface effects
- lower coordination number
- broken magnetic exchange bonds
- frustrated magnetic interactions
- surface spin disorder
- reduced \( M \) in ferri-, antiferro-systems
- enhanced \( M \) in metallic ferro-systems

Spin glass? Dead magnetic layer? Bulk-like?
Ensembles vs Single-Particle Properties

**Ensembles:**
Distributions with respect to nanoparticle size, aspect ratio, crystalline structure, defect distribution, and chemical composition.

**Single Particle experiments:**
Correlate the electronic, magnetic, and structural properties with the size, aspect ratio, crystalline structure, and chemical composition of each individual particle.

The ability to manipulate a single nanoparticle has an increased potential in device manufacturing.

Courtesy of M. Farle, Uni Duisburg
### Single Particle Detection: Techniques Available

<table>
<thead>
<tr>
<th>Technique</th>
<th>( \Delta x ) (nm)</th>
<th>E-resolution (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-STM</td>
<td>0.5</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>EELS</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Optical Fluorescence</td>
<td>&lt; 5</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**XPEEM**

<table>
<thead>
<tr>
<th>Technique</th>
<th>( \Delta x ) (nm)</th>
<th>System (Individual Particles)</th>
</tr>
</thead>
</table>
| XPEEM     | 50                   | • InAs (D~50 nm), \( \Delta E/E=0.2 \) eV, Heun et al.  
• Fe\(_2\)O\(_3\) (D ~ 10 nm), \( \Delta E/E=0.5 \) eV, Rockenberger et al. |
Soft x-ray Spectromicroscopy

Chemical Selectivity
- Fe, Co, Ni
- Intensity (a.u.) vs. Photon Energy (eV)
- Chemical bonding, electronic properties

Surface and interface sensitivity
- Vacuum, secondary electrons, sample surface
- Photon penetration depth ~ 50 nm
- Electron escape ~ 5 nm depth

Magnetic Contrast: XMCD
- Photon energy (eV)
- TEY (a.u.)
- Magnetic contrast: XMCD
- Atomic magnetic moments

Magnetic Contrast: XMLD
- Photon Energy [eV]
- Intensity [a.u.]
- Antiferromagnets
Soft x-ray Spectromicroscopy

Element specific imaging: PEEM

Co islands, 778.1 eV
Py film, 852.7 eV

Co
Py
Substrate

Magnetization Direction

5 μm
- probing secondary/Auger/photoemission
- spatial resolution: 50 nm
- electron energy resolution: 0.1 eV
- $H_A \approx 30$ mT
- $100 \, K < T < 1500 \, K$
- ultra high vacuum
Cobalt particles: Arc ion cluster source

- particle size tunable between 4-15nm
- size distribution: $\Delta D/D \sim 10-15\%$
- *in situ* deposition

Collaboration with J. Bansmann, Uni Ulm, and A. Kleibert, Uni Rostock

- deposition of Co particles on Si substrates
- coverage: 5-10 particles/μm²
- lithographic markers on substrates
- low percentage dimers/trimers
- crystalline structure

Lithographic markers: L. J. Heyderman, PSI
Elemental Contrast: X-ray PEEM

Co particles D ~ 13 nm oxidized in air

Photon energy 778 eV

Photon energy 770 eV

Image (778 eV)/ Image (770 eV)
Co particles D \(\sim 8\) nm / 8 nm Al capping layer

The lithographic markers are essential to correlate unambiguously the PEEM observations with the size of the particles imaged by the SEM.

Lithographic markers: L. J. Heyderman, PSI
Individual Particles: X-ray Absorption Spectra

Co particles D ~ 8 nm, no capping layer

Movie: 159 images
Total acquisition time: 12 hours.
Co particles D ~ 8 nm, no capping layer

![Graph showing X-ray Absorption: Particle-to-particle variation](image)

Adapted from Regan et al. PRB 64 (2001) 214422
Co particles D ~ 8 nm, no capping layer

Intensity (arb.units)

Photon Energy [eV]

Reference CoO thin film

Adapted from Regan et al. PRB 64 (2001) 214422
• in situ Fe clusters (~ 9 nm) supported on ferromagnetic thin films

• alloy systems, e.g. Fe$_x$Co$_{1-x}$, Fe$_x$Pt$_{1-x}$

• Magnetic transition temperatures on the nanoscale
Conclusions

• X-ray absorption spectra of individual Co particles as small as 8 nm

• Differences in oxide-related features between individual particles were observed

• Changes between the spectra of an individual particle and the ensemble were observed
Collaborators

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