Neutron scattering studies of catalyst systems at the ISIS neutron spallation Source

October 29th 2014

2nd World Congress on Petrochemistry and Chemical Engineering



Martin Owen Jones

ISIS Facility, Rutherford Appleton Laboratory

ISIS

Science & Technology Facilities Council

The Nobel Prize in Physics 1994

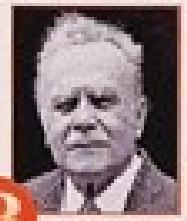


Neutrons behave as particles and as waves

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.

Neutrons reveal structure and *dynamics*



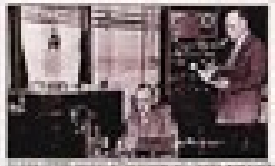


Neutrons show where atoms are

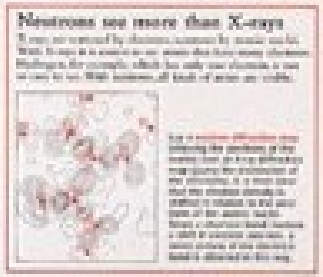
Neutrons show what atoms do

Neutrons bounce against atomic nuclei. They also react to the magnetism of the atoms.

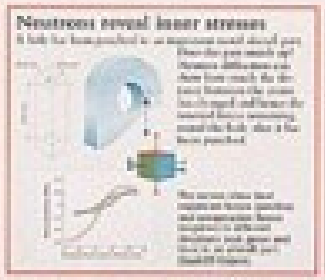
Research reactor







Neutrons see more than X-rays



Neutrons reveal inner stresses



Neutrons show what atoms remember



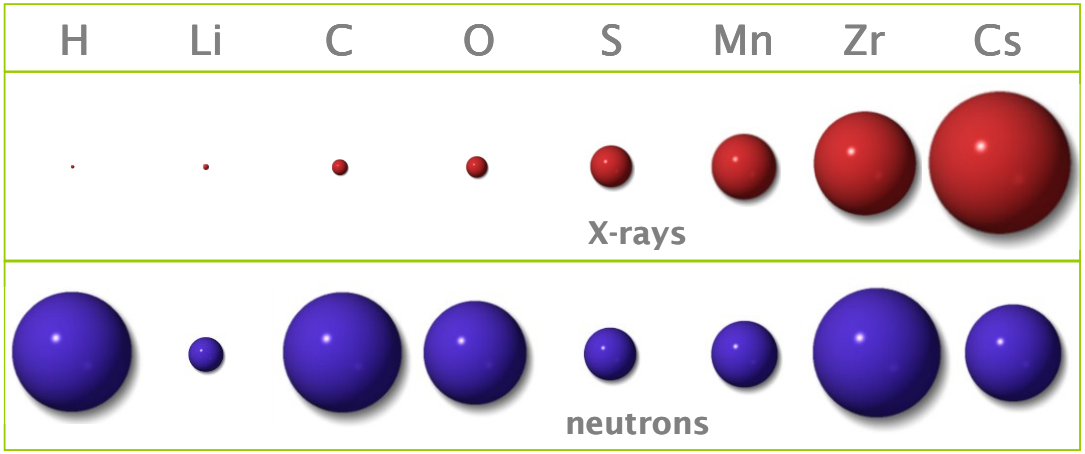
KUNGL VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Further reading

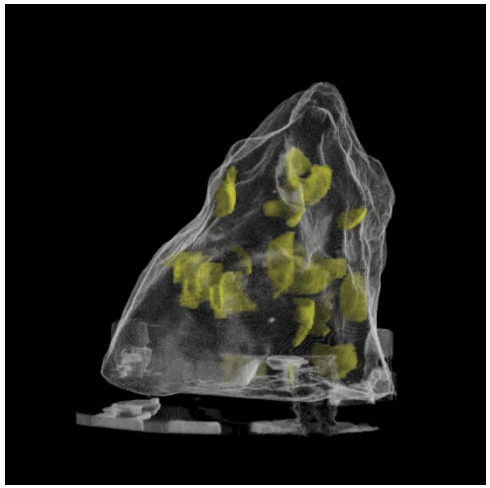
’Neutrons tell you where atoms ***are*** and what atoms ***do***’

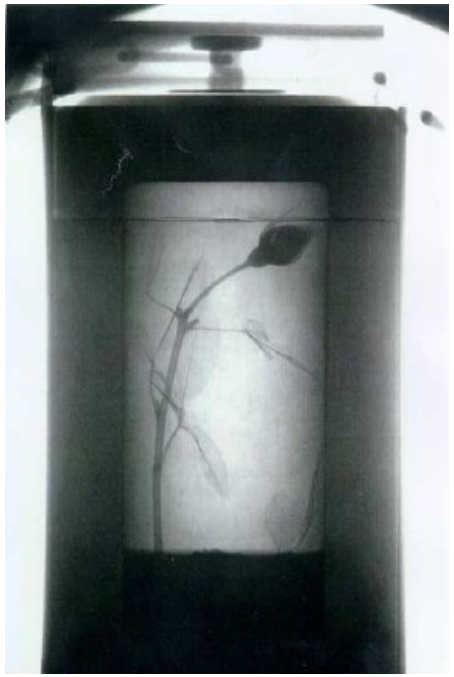
Neutrons – a tailor-made probe

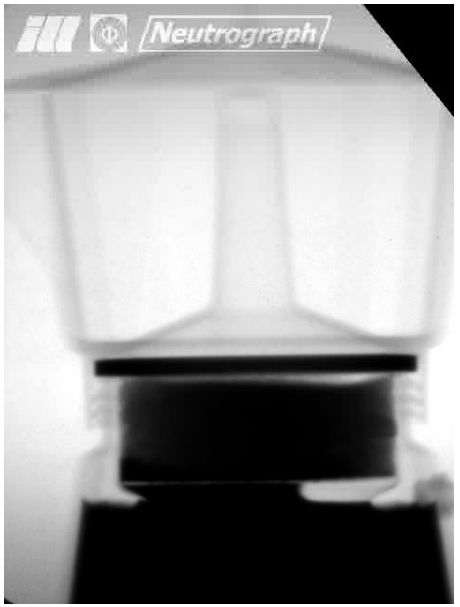
- Neutron wavelength and energy ‘just right’ for condensed matter
  - *– structure and dynamics*
- Neutron cross-section
  - *–isotopic dependence*
- H / D contrast
  - *–nuclear form factor*
- Magnetic Moment
  - *–magnetic order & excitations*
- Weak probe
  - *–theoretical interpretation*
- Highly penetrating
  - *–bulk probe*
  - *–complex SE*



Neutrons see the world in a *unique* way







Penetration

Large samples, buried interfaces, non-destructive

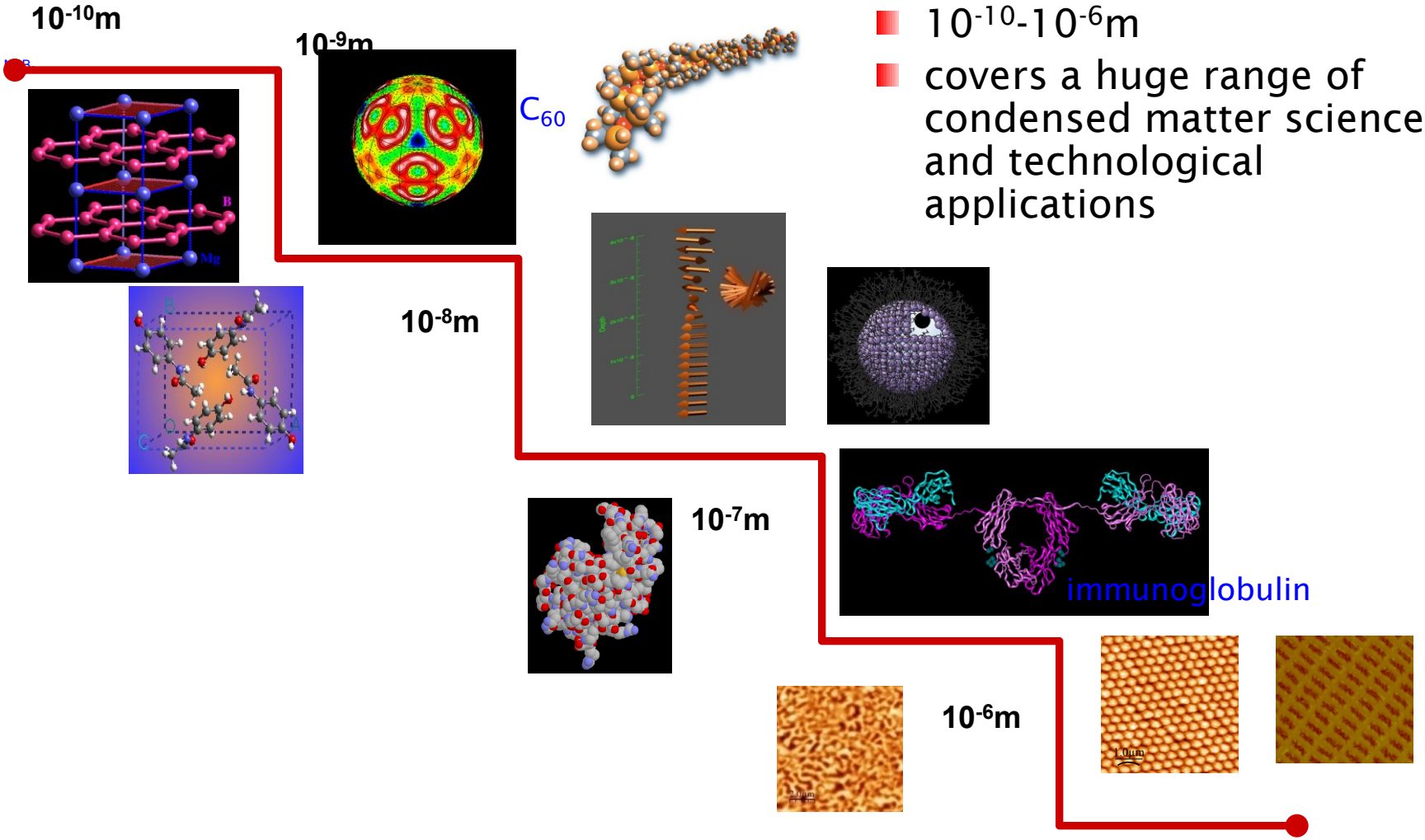
No One Experiment



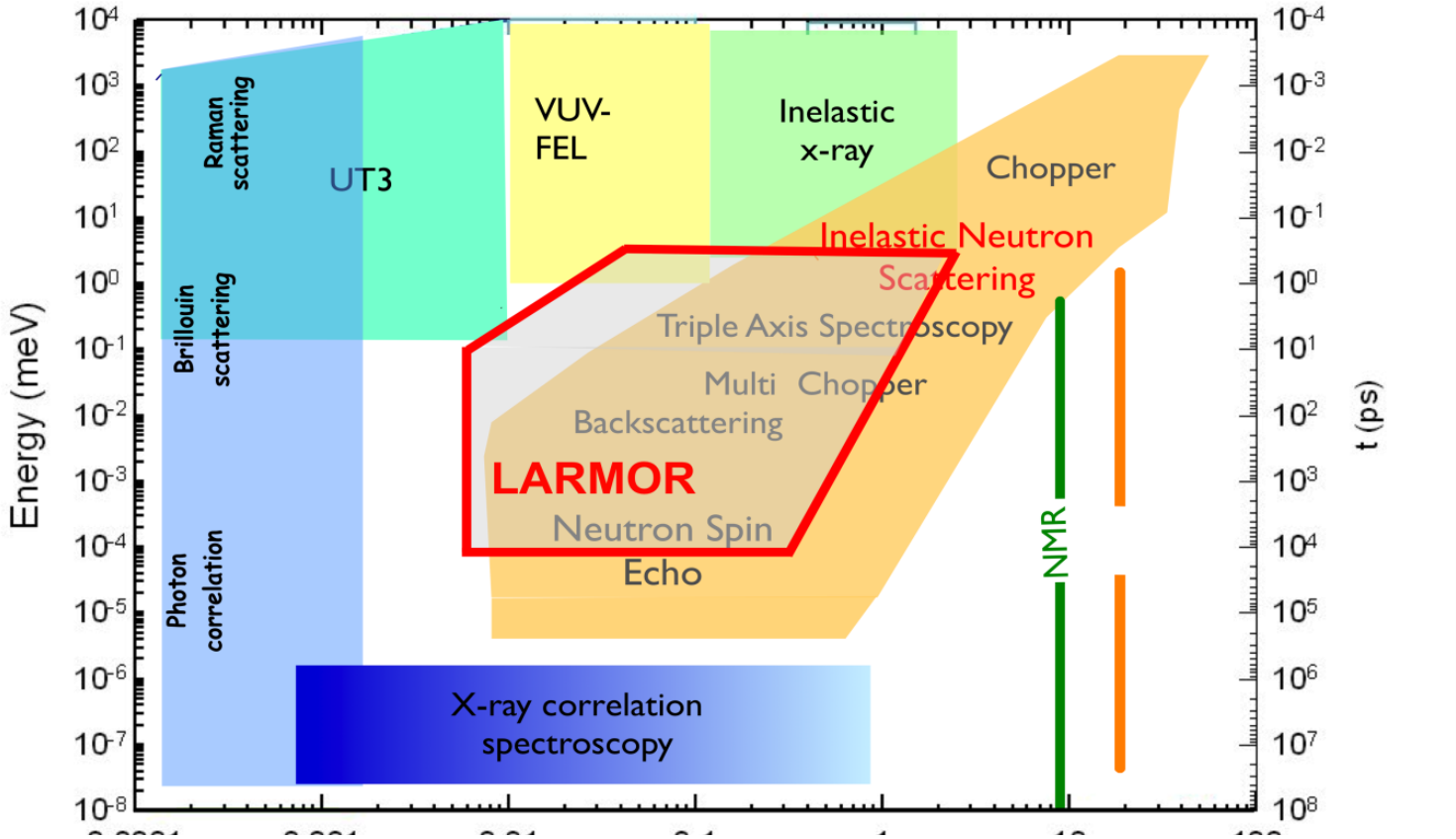
Achievements of neutron scattering
– the evolution and diversification of neutron scattering over the past 40 years

The *relevant* lengthscales

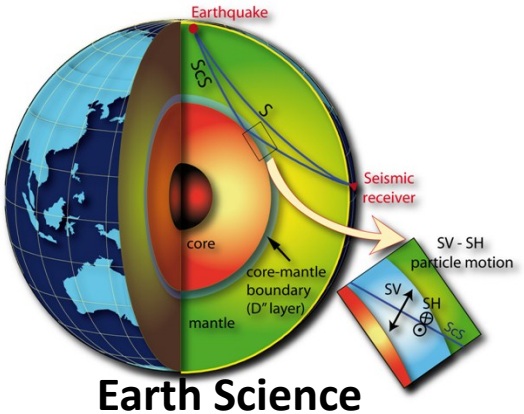
- The length scale from
  - 10^{-10}-10^{-6}m
  - covers a huge range of condensed matter science and technological applications



Energy Scale



Science & Technology Facilities Council
ISIS



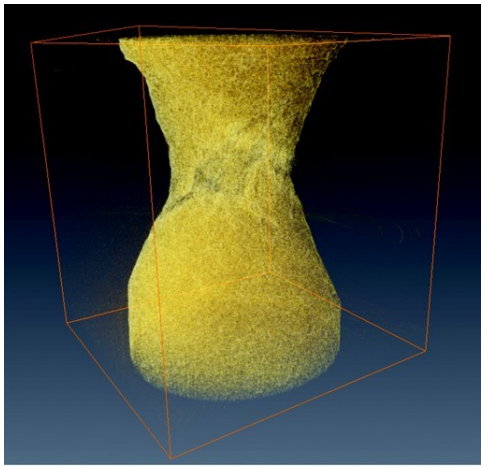
Earth Science

Studying ferropericlase helps understanding of earthquakes



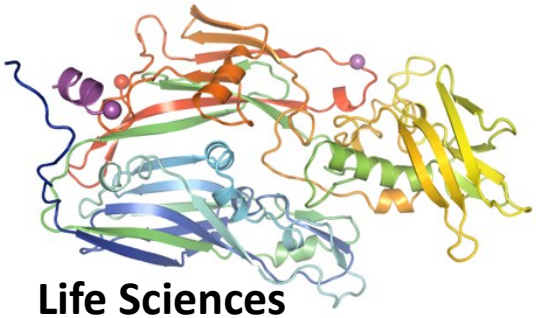
Cultural Heritage

understanding molecular processes of preservation of polychrome carved wood



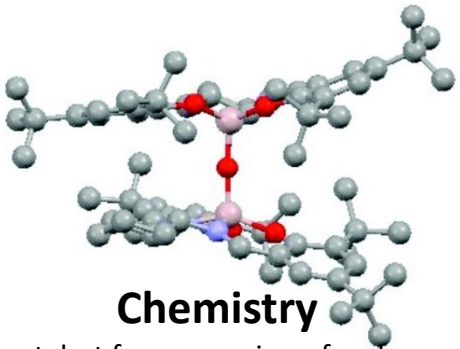
Engineering

3-D high speed tomography



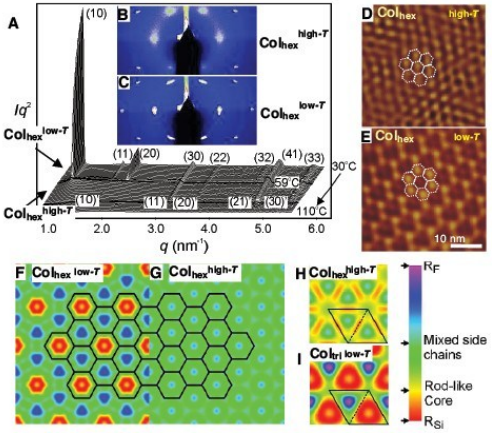
Life Sciences

Structure and history of viruses



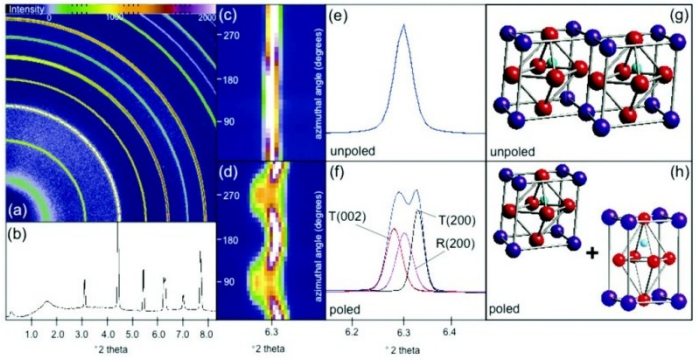
Chemistry

catalyst for conversion of carbon dioxide to cyclic carbonates



Physics and Materials Science

Magnetic contrast imaging for FeRh films

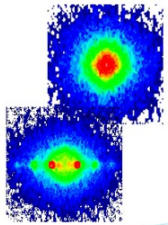


Environmental Science

Electric-field-induced phase transformations in lead-free piezoelectric ceramics

Process optimisation of fabric care products

- Anglo-Dutch multinational with **global home, personal care & food product** markets in over **50 countries**
- Annual **turnover €40 billion**
- UK **fabric conditioner** market **€250M**
- **Neutron scattering** measurements used to **optimise processing conditions**, reduce process time and energy, and improve **product quality**
- **Experiments** at ISIS have yielded **significant cost savings**





"Neutron scattering measurements are used to optimise processing conditions, reduce process time and energy, and improve product quality."
– Unilever



Comfort

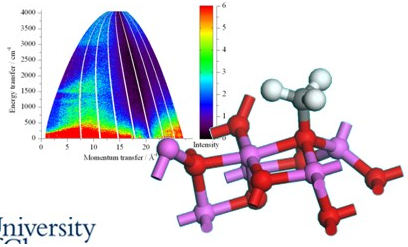
Unilever

I. J. Tucker et al., Langmuir, (2009) 25 4934-4944

Methyl chloride synthesis:Neutrons help industry

- **INEOS ChlorVinyls** major European chlor-alkali producer and **Europe's largest** PVC manufacturer
- **Methyl chloride** synthesis at **Runcorn** is a major process – **120,000 tonnes** per year
- Dimethylether **waste product** energy intensive and **expensive to recycle** to methanol
- Neutrons enabled **modification** of alumina **catalyst**
- Cost **saving of £4,000,000 per year** and less CO_2



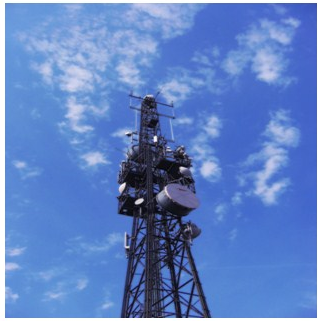


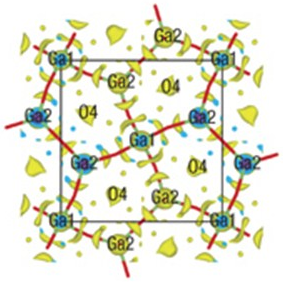
University

"Infrared spectroscopy only shows what is on the surface of the catalyst, but neutrons give the whole picture. We were able to modify the catalyst to give 50% less unwanted derivative."
–Dr Stewart Parker, ISIS and Professor David Lennon, University of Glasgow

ISIS helps mobile phone component manufact

- **Mobile phones** and base stations contain **ceramic antennas** called dielectric resonators
- **ISIS recreated the firing stage of ceramic components** at more then 1000 °C
- Testing at ISIS has **aided manufacture** of ceramic resonators to the **correct specification.**





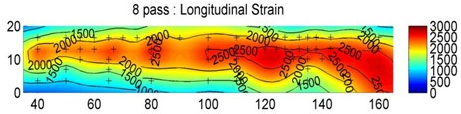
"ISIS, in collaboration with Liverpo
University, generated the intrinsi
necessary for the understanding
structure of these complex mater
– David Iddles, Powerwave UK,
Ceramics Development manager

Powerwave technologies

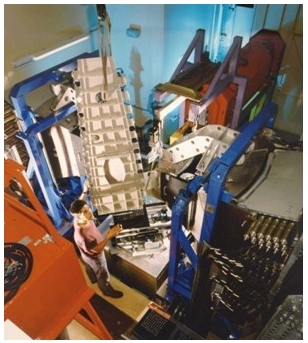
R.M. Ibberson et al., J Am Ceram Soc (2006) 89 1827-1833

Wing quality soars at ISIS

- **Aircraft manufacturer Airbus has used ISIS since 2006**
- Research into **aluminium alloy weld integrity** for aircraft programmes
- **Residual stresses** from welding cause weaknesses and the possibility of cracks
- ISIS **neutrons look deep inside engineering components** to measure stress fields



AIRBUS



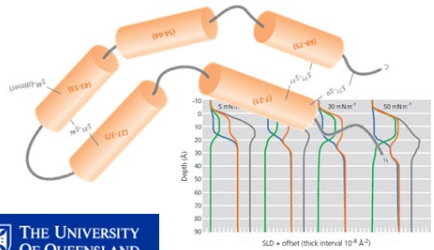
"Residual stress measurement at ISIS has been invaluable in researching and developing existing and novel material manufacturing and processing techniques ."
– Richard Burguete, Airbus
Experimental Mechanics Specialist

E.Oliver et al., Meas. Sci. Technol. (2008) 19 034019

Understanding infant lung structure

- Natural **lung surfactant** allows **oxygen** into the bloodstream
- Absence in **premature babies** causes **breathing difficulties**
- ISIS mimicked change in lung capacity to discover how **proteins** and **phospholipids act together**
- Helping to **develop synthetic lung surfactants** which can be more **precisely targeted** at clinical needs to help **save babies'** lives





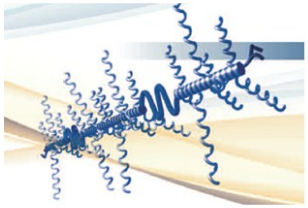
"ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function."
- Dr Stephen Holt, ISIS neutron scientist

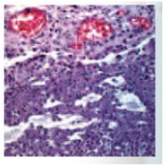
THE UNIVERSITY OF QUEENSLAND AUSTRALIA

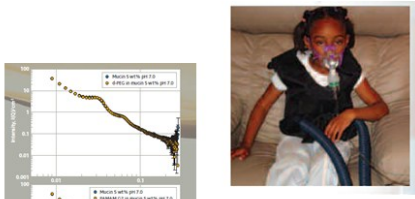
D Follows et al., Biochim Biophys Acta Biomembr (2007)2 228

ISIS helps to explore drug delivery

- **Mucin** is found in respiratory, gastro-intestinal and reproductive tracts.
- **Cystic fibrosis increases the thickness** of mucin, making drug treatment difficult
- **Polymer therapeutics** uses long-chain molecules to **deliver drugs to particular locations** in the body
- **Polymer diffusion** through **mucin** studied at ISIS







"Neutron scattering indicates that the mucin structure collapses in the presence of the polymer therapeutics"
-Paola Occhipinti, Cardiff University

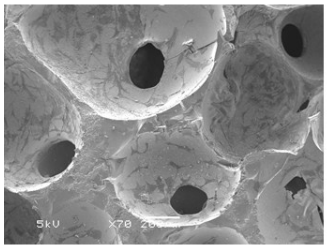
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

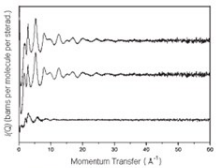
BBC cymru wales
Science Café

P.C. Griffiths et al., Biomacromolecules, (2008) 9 1170

Bioactive glass for bone growth

- Thousands of **elderly patients** undergo hip or knee **transplants** every year
- New bioactive glass releases **calcium** as it dissolves
- **Stimulates bone growth** and could spell an end to transplants
- **Clinical trials** expected **within 5 years.**
- **Imperial, Kent, Warwick, NHS**





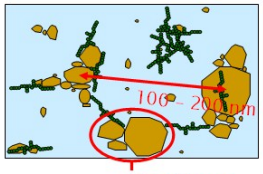


"ISIS has enabled us to move forward with the programme. The key outcome of our experiments has been a full understanding, at the level of atomic arrangements, of why it is that calcium is able so easily to leave the glass at the rate required to generate the desired response."
-Bob Newport, University of Kent

L.J. Skipper et al., J Mat Chem (2005) **15** 2369

Clear as muddy water

- **Nanoparticles** in household cleaners, toothpastes, sunscreens, and foods **affect the aquatic environment**
- ISIS studies river water samples to **help improve water resources** across the European Union
- **Neutrons view organic and inorganic particles,** unlike X-rays which only show the inorganic materials
- **Nanoparticles** have much **higher surface area** than **previously thought.**
- **Greater potential for pollutant uptake** and transport





"We can see the behaviour of these nano particles in real river water samples, rather than viewing them in the lab, which alters their structure"
-Dr Helen Jarvie, NERC Centre for Ecology and Hydrology

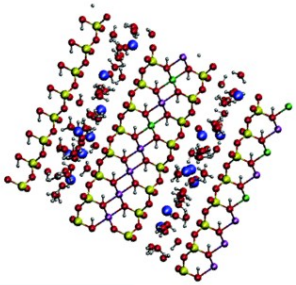
CEH Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

S.M. King et al., Environ Sci Technol (2007) 41 2868

ISIS helps unclog the cholesterol of crude oil

- **Asphaltenes** are a complex mixture of molecules that can sometimes **block oil pipes**
- Research to more easily **predict** and **prepare** for the formation of asphaltene deposits
- Result in **fewer blockages** and **big savings** for the oil industry.





"ISIS allowed us to understand more clearly how asphaltenes aggregate, an important observation from a flow assurance point of view and should allow more efficient extraction of hydrocarbons in the future."
–Edo Boek, Schlumberger Cambridge Research, Senior Research Scientist

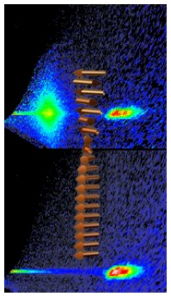
Schlumberger

Spintronics for IT, automotive and health sectors

- **Spintronics** underpins applications as diverse as **biosensors** for blood screening, **computer memory** and **safety systems** for cars
- Potential for smaller, faster devices with **more capacity** and **lower power** consumption
- Most **promising materials** for future devices only work at **low temperatures** and **high magnetic field**
- ISIS **supporting global efforts** through **Spin@RT** consortium of UK universities and industry



Seagate
TOSHIBA
Leading Innovation
HITACHI
Inspire the Next

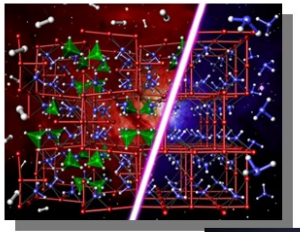


"Many of the most promising materials to deploy in future devices only work under extreme conditions. ISIS gives a unique nanoscale understanding of the materials in the quest to make them work at room temperature."
– Sean Langridge, ISIS Senior Fellow, Visiting Professor University of Leeds

ISIS contributes to zero-emission vehicles

- **Hydrogen-powered cars** are **feasible** using today's technology
- Harmful **emissions** reduced to **zero**
- Method of **safe**, **low-cost hydrogen storage** on-board **holding up deployment**
- **Hydrogen-rich solids** safely releasing hydrogen developed using ISIS neutrons
- **New materials** hold upwards of **10 percent** of their own **weight** in **hydrogen**





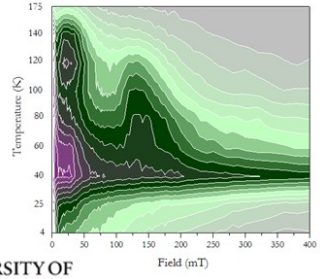
"We've discovered new sets of material that can store hydrogen more efficient than hydrogen itself. Neutrons are wit doubt the best way to see hydrogen entering and leaving in real time."
–Professor Bill David, ISIS Senior Scienti

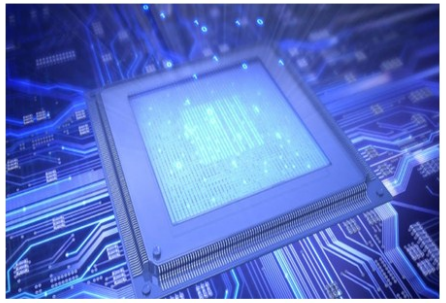
UK-SHEC EPSRC
Technology Strategy Board
Driving Innovation

P.A. Chater et al., Chem Commun, 2439–2441 (2006)

Muons, hydrogen and semiconductors

- **Transparent semiconductor** zinc oxide could play a vital part in new applications such as **energy-efficient white lighting**
- Semiconductors often grown by **hydride gas deposition**
- **Hydrogen** can **impair** conductivity
- **Muons** can be used to **measure** how **hydrogen defects** behave inside semiconductors





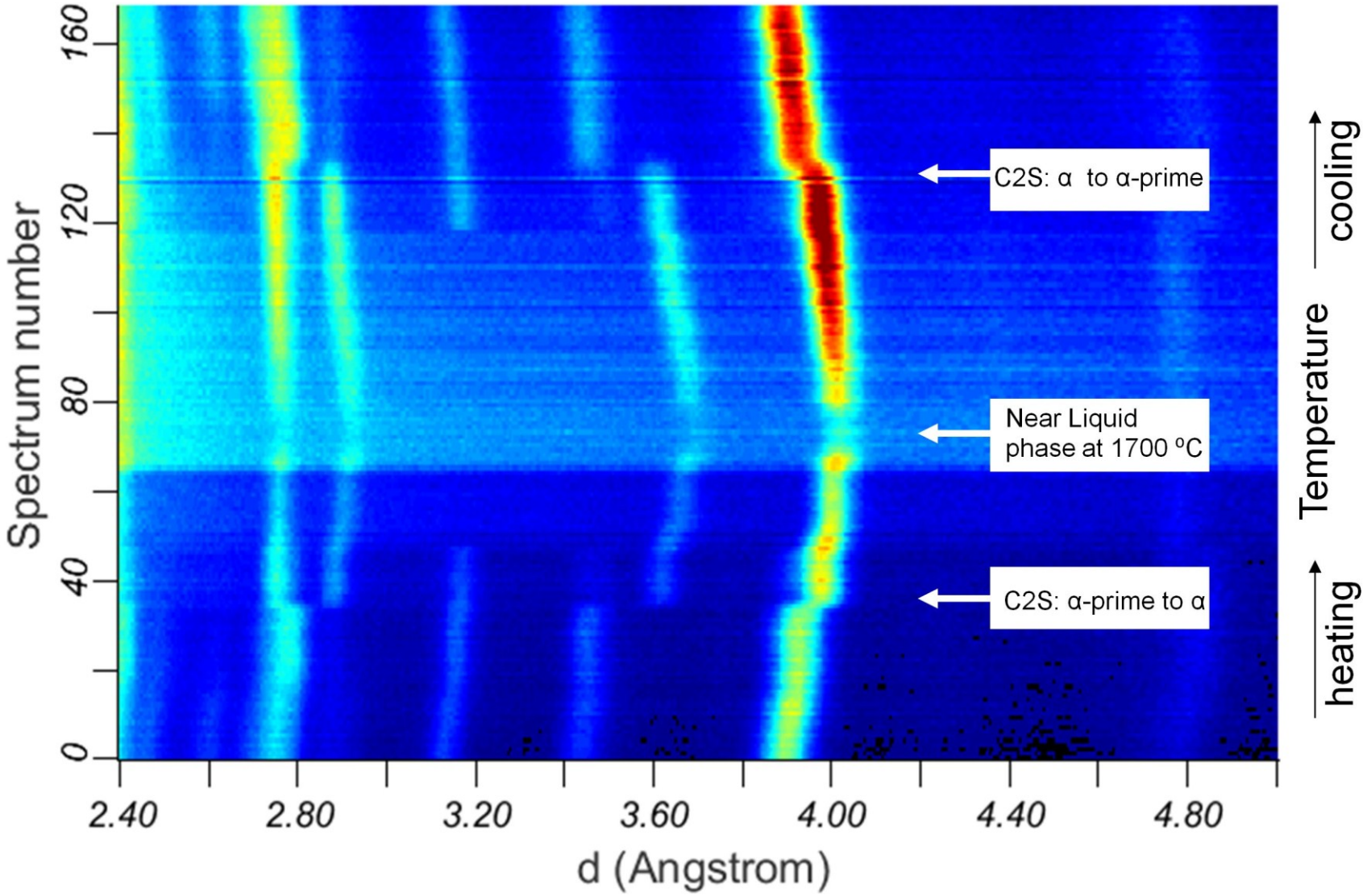
"Muonics remarkable selectivity and sensitivity allows us to confirm the action of hydrogen on the conductivity of zinc oxide and other semiconductors."
–Professor Steve Cox

UNIVERSITY OF CAMBRIDGE
University of Coimbra

S.F.J. Cox, J. Phys Condensed Matter, (2006) 18 1079

GEM : PHASE TRANSFORMATIONS IN STEEL

Phase formation at temperatures up to 1700°C (Tata steel).

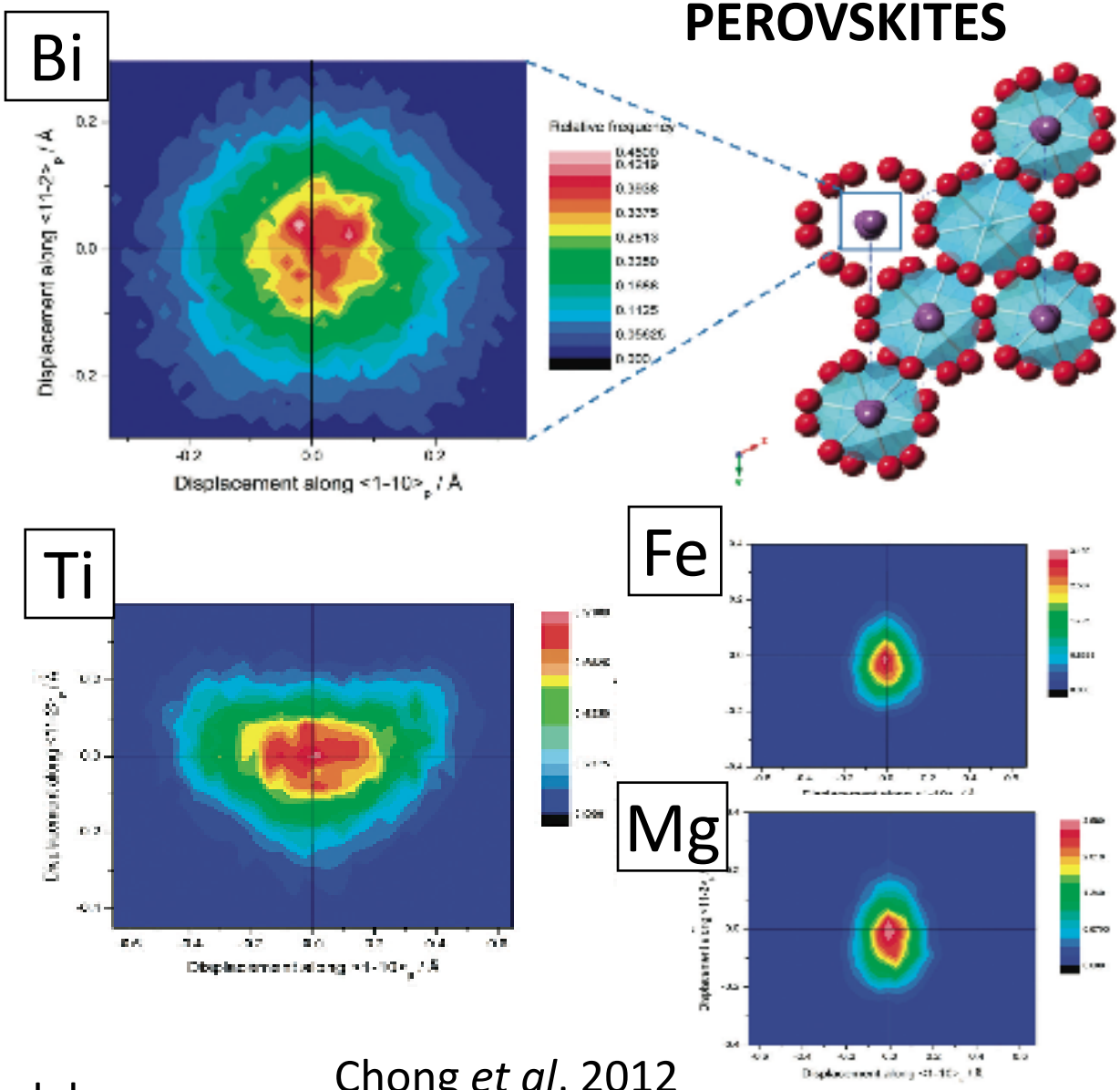


GEM : LOCAL STRUCTURES IN PEROVSKITES

$Bi(Ti_{3/8}Fe_{2/8}Mg_{3/8})O_3$ possible lead-free replacement for PZT piezoelectric material.

RMC modelling of provide insights into several unexplained aspects of earlier crystallographic studies.

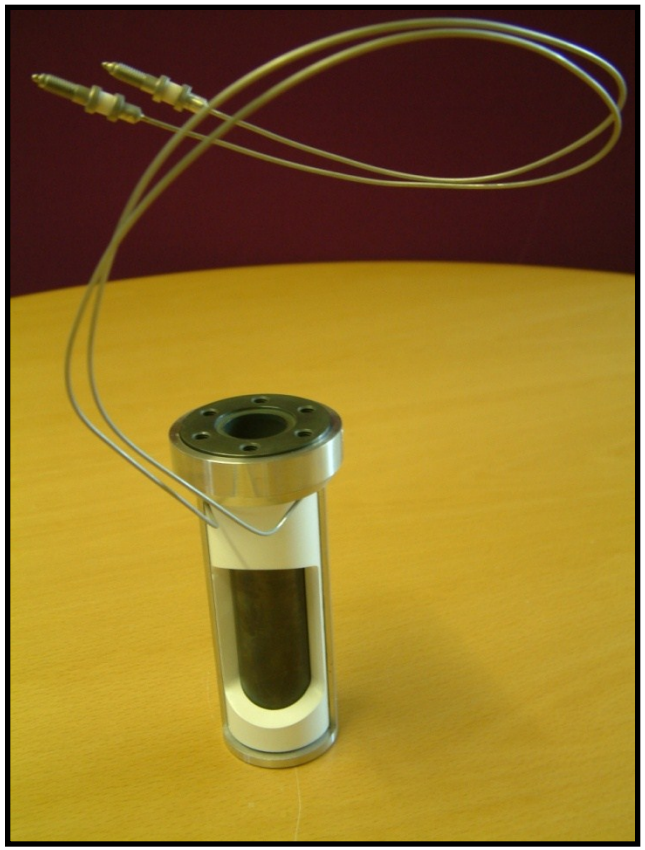
Locally monoclinic clusters accounts for micro-strain broadening required for Rietveld refinement using the rhombohedral structural model.



Chong *et al*, 2012

POLARIS : REACTION CELLS

Exploit the high count rate of the new Polaris to monitor chemical reactions in-situ.

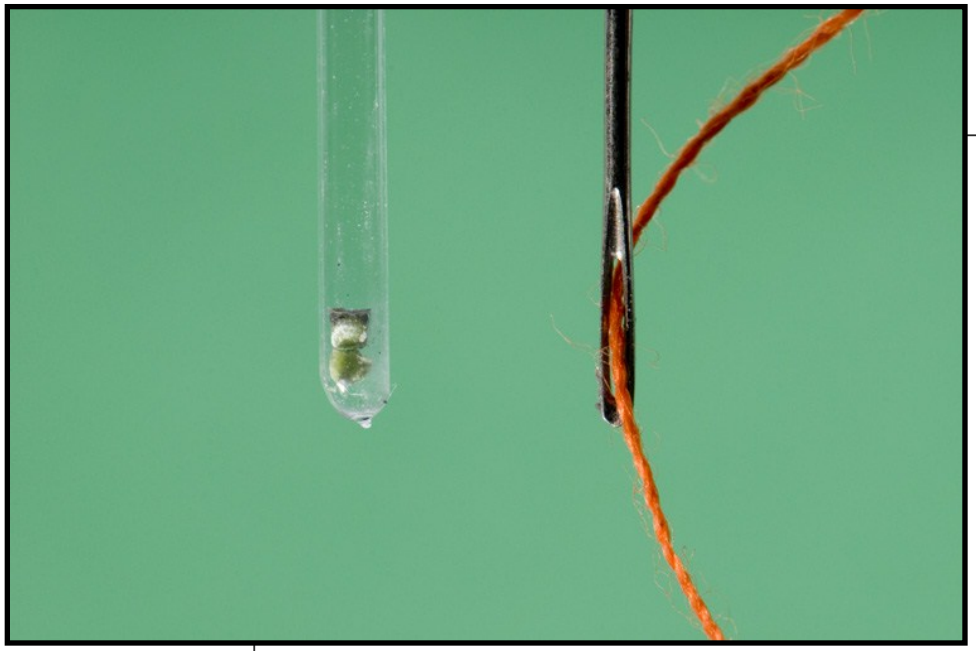


Supercritical hydrothermal cell (Korea + Oxford + ISIS).



In-situ microwave synthesis (Glasgow + ISIS).

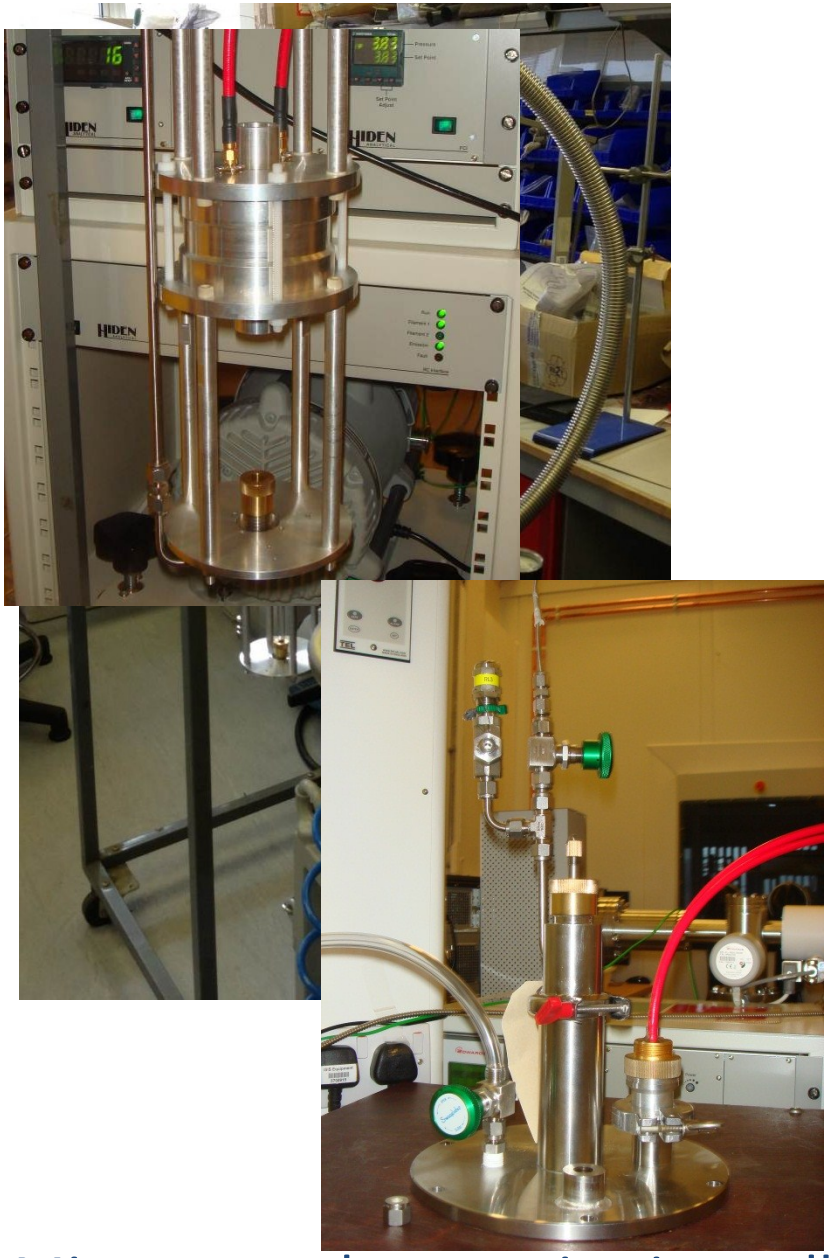
POLARIS : SMALL SAMPLE VOLUMES



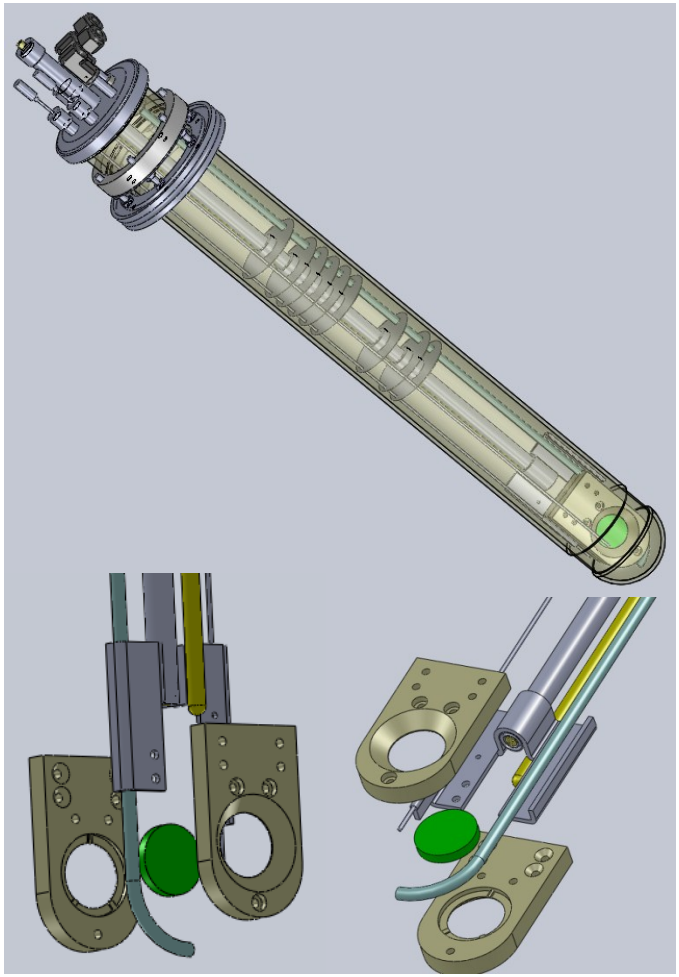
~1mm^3 samples of $NaNiF_3$ phase prepared at high p + high T

POLARIS : REACTION CELLS

In progress

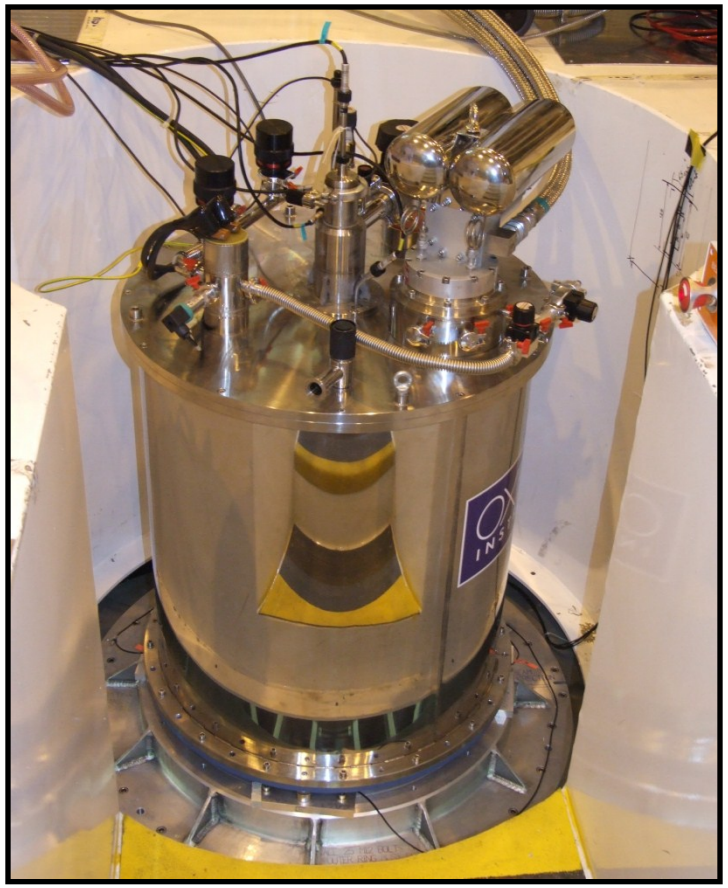


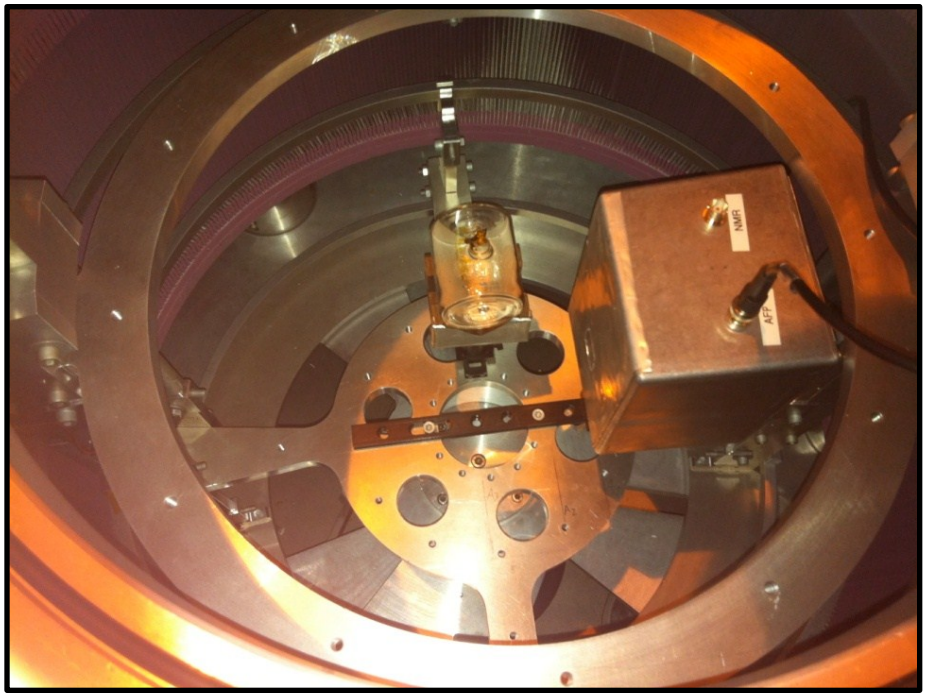
Microwave characterisation cell
(Cardiff + ISIS).

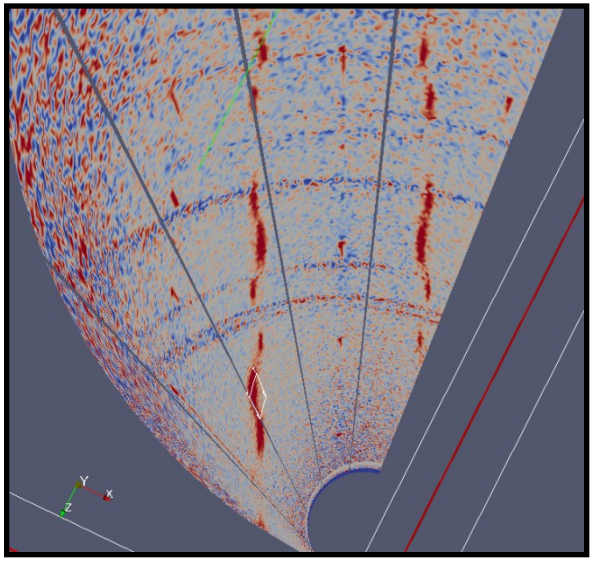


Concentration cell
(St Andrews + ISIS).

WISH : DEVELOPMENTS







14T superconducting magnet.

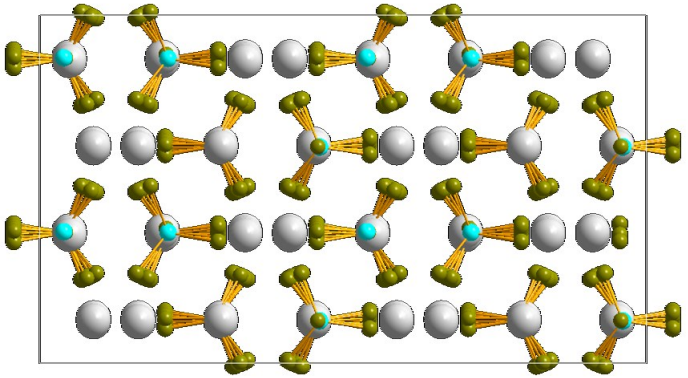
30T pulsed magnet.

Polarization tests underway.

Diffuse scattering software.

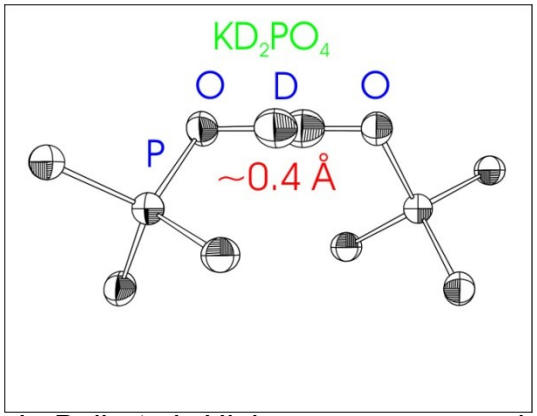
Enabling high-profile studies

Modulated structures



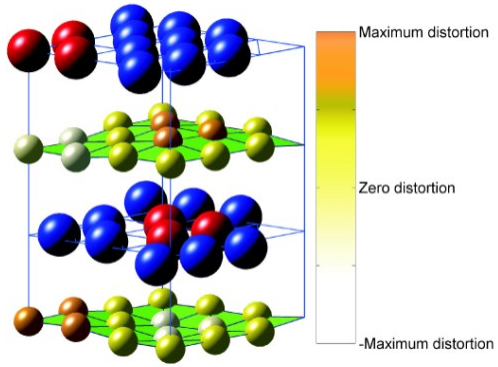
M. J. Gutmann *et al.*, Measurement Sci Technol **19**, 034005 (2008)

High-pressure studies



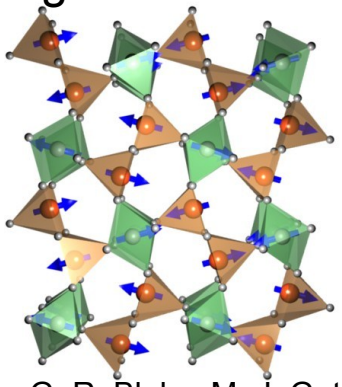
C. L. Bull *et al.*, High pressure research **29**, 780 (2009)

Complex superstructures



M. Roger *et al.*, Nature **445**, 631 (2007)

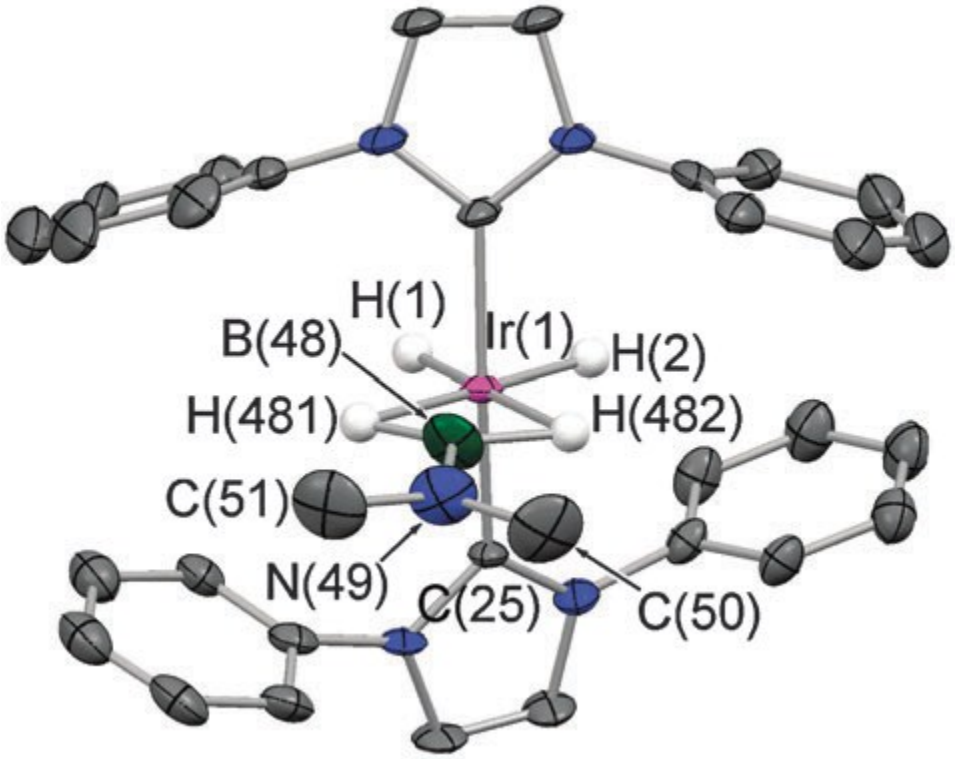
Magnetic structures

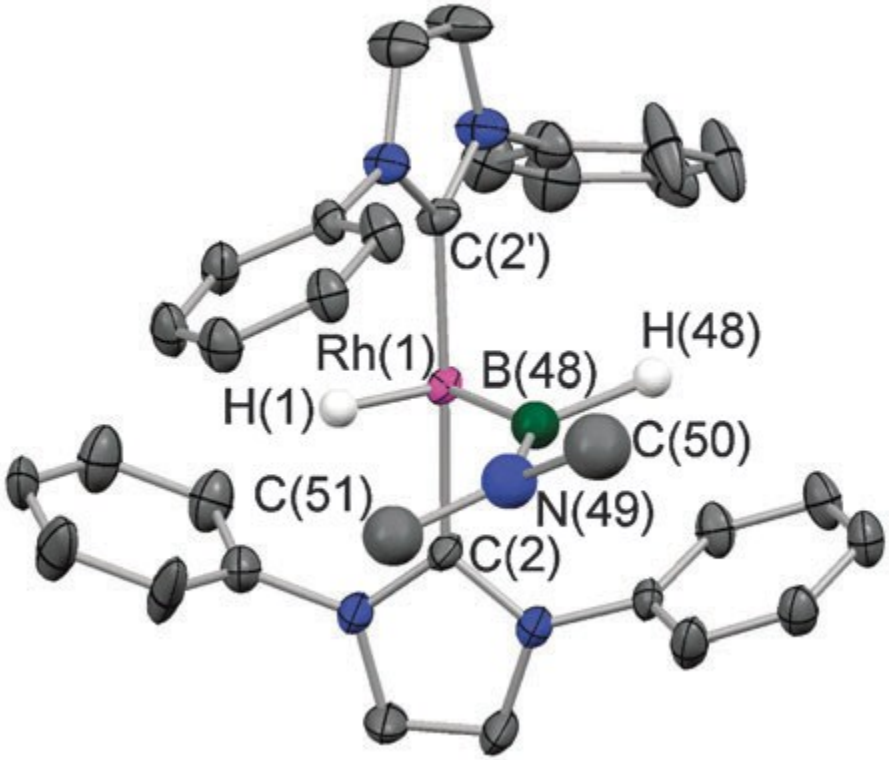


L. C. Chapon, G. R. Blake, M. J. Gutmann *et al.*, Phys. Rev. Lett. **93**, 177402 (2004)

SXD : LOCATING HYDROGEN

Dimethylamine borane dehydrogenation.





18-electron aminoborane adduct

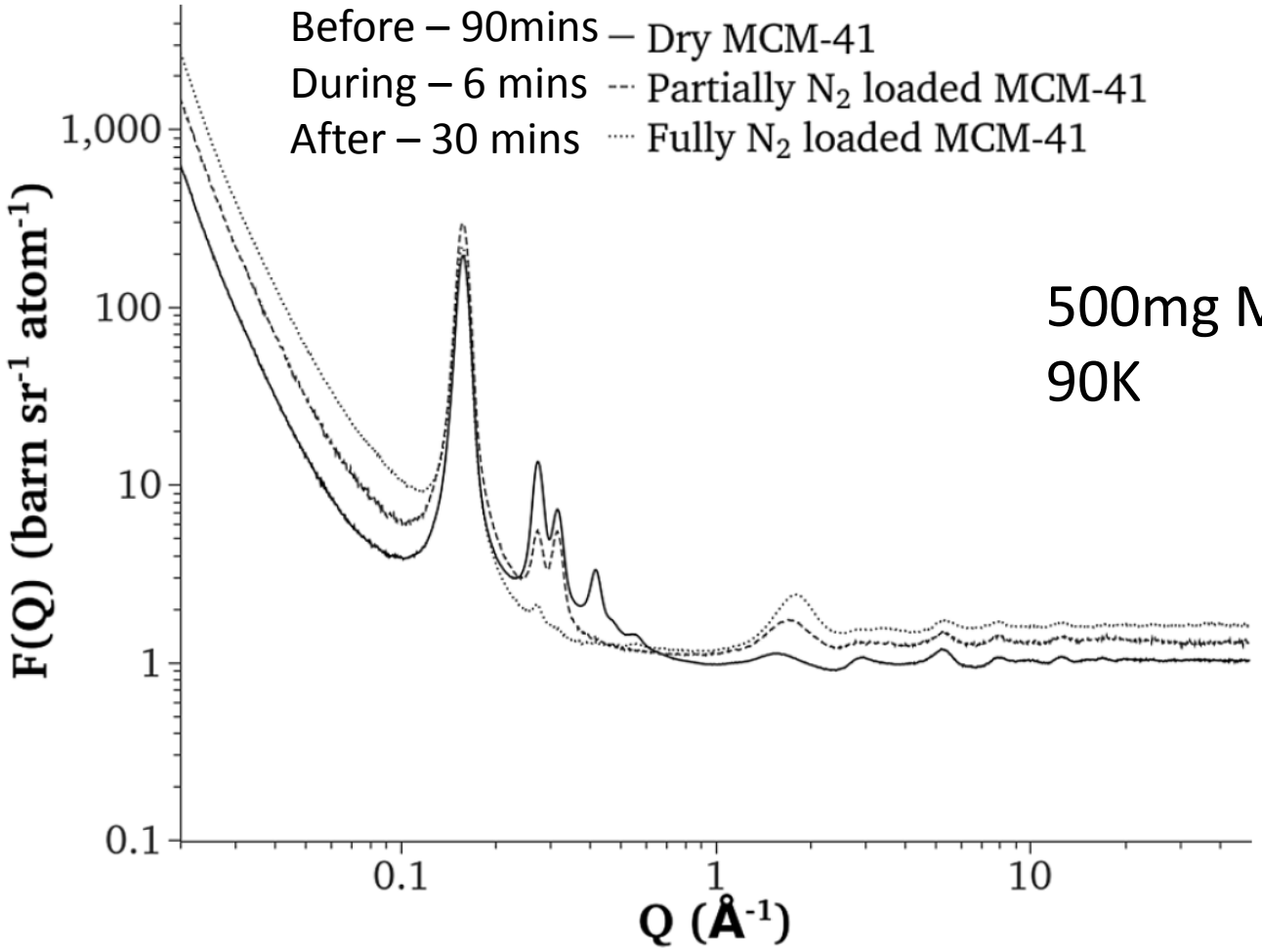
14-electron aminoboryl complex

SXD used to determine positions of H-atoms in metal complexes formed under catalytic conditions.

Tang *et al.* (2012)

Amorphous Materials – Porous Materials

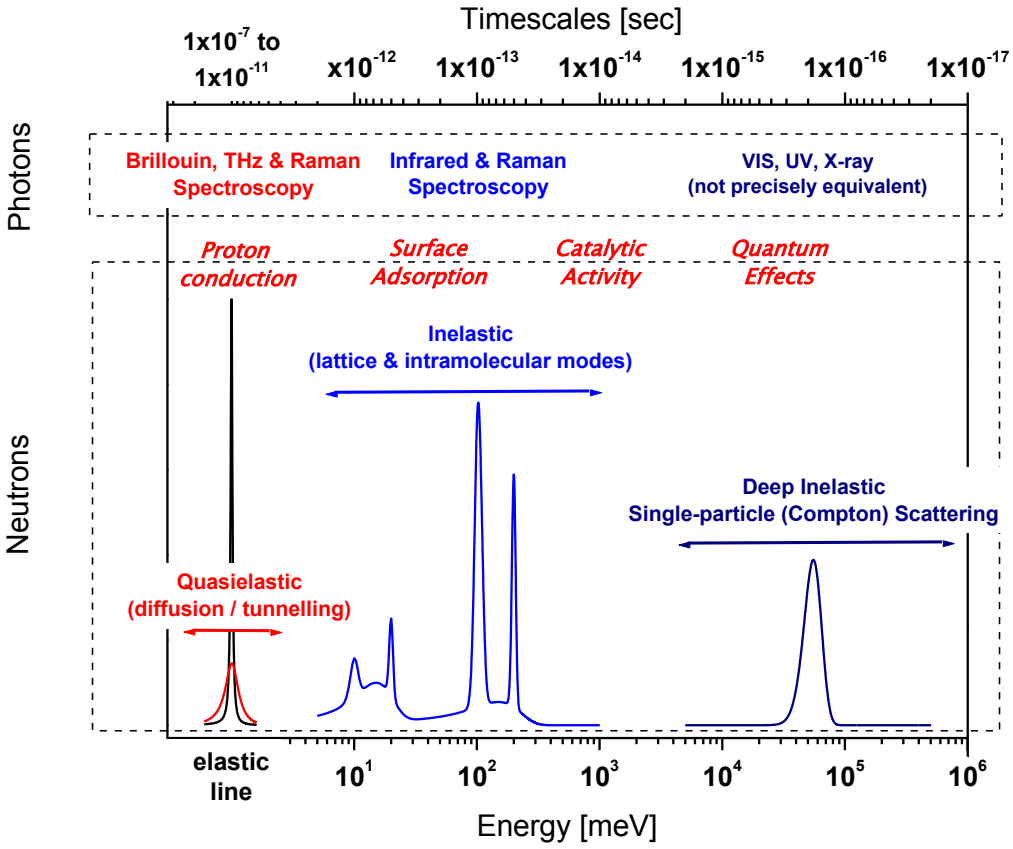
ostructure

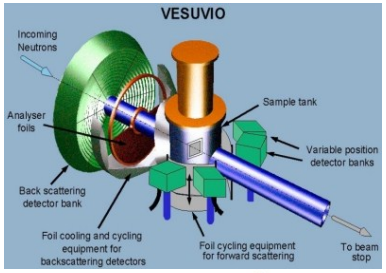


500mg MCM-41
90K

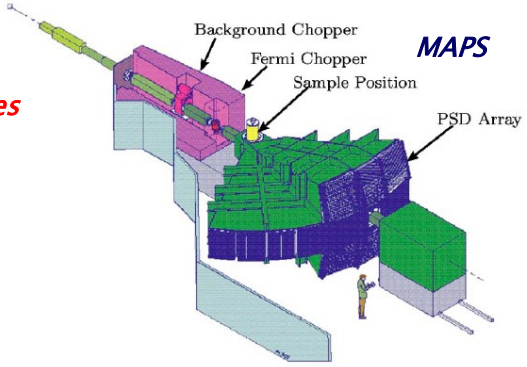
NIMROD

Chemical Spectroscopy at ISIS





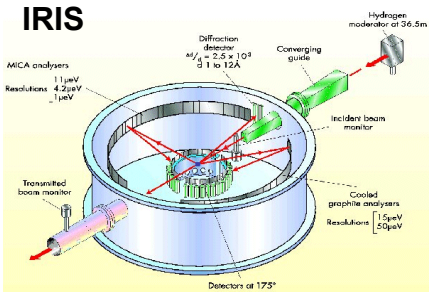
Simultaneous high-resolution diffraction



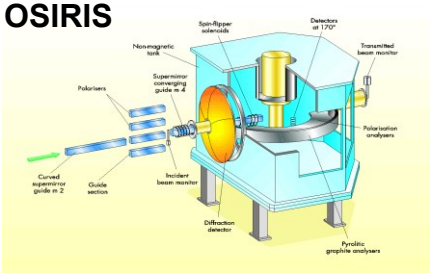
High energies

Widest spectral range in the world

IRIS

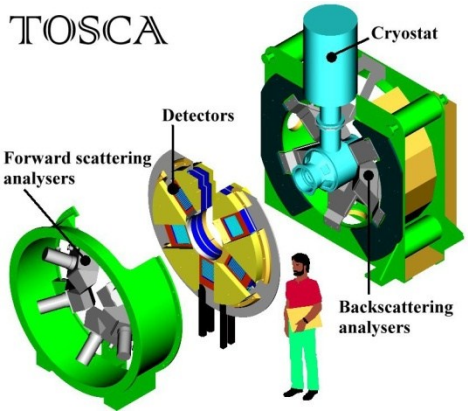


OSIRIS



Low energy (Brillouin, THz)

TOSCA



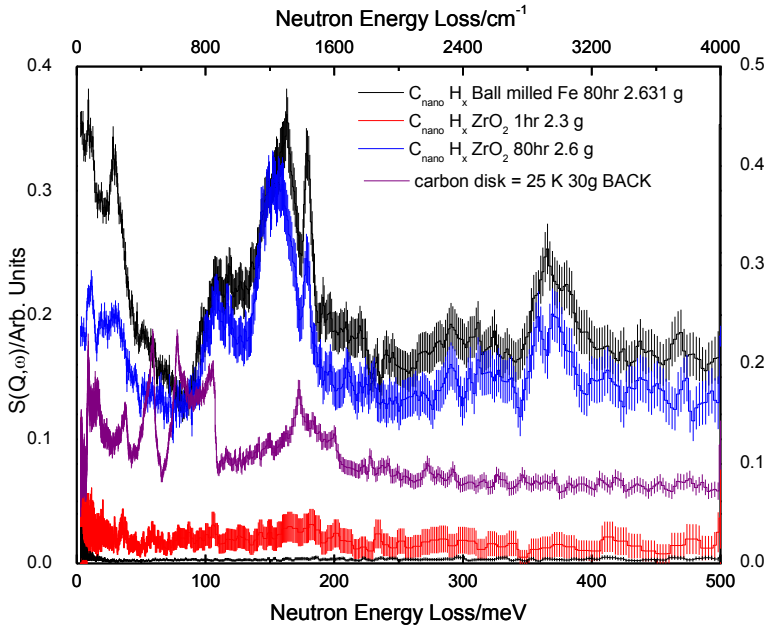
Intermediate energies (infrared, Raman)

Molecular motions of adsorbed species

Inelastic and quasi-elastic studies for molecular motions of adsorbed species

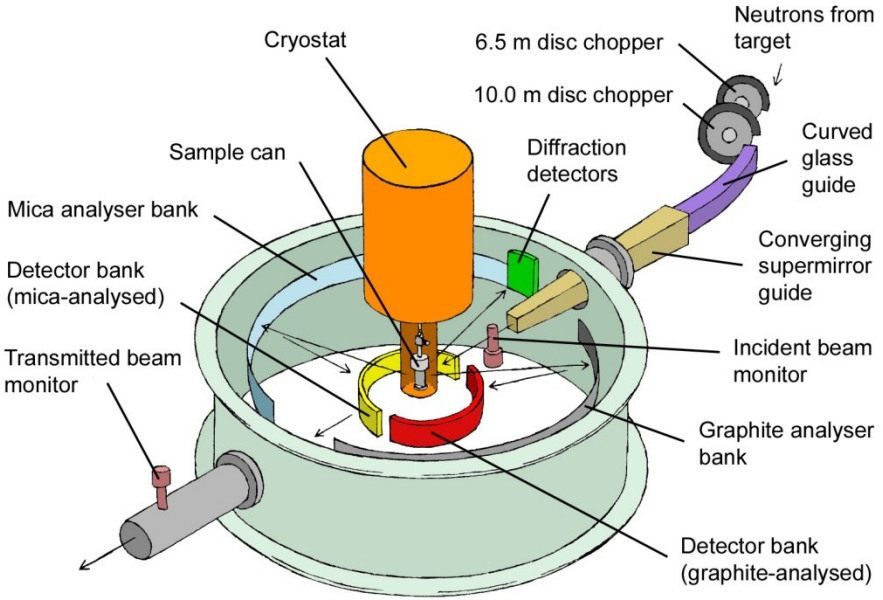
Identify the interaction of hydrogen containing species with catalysts and host materials

Time and length scales match those of molecular simulation – combined analysis is possible



TOSCA spectra of hydrogenated nanoscale graphite

IRIS Spectrometer

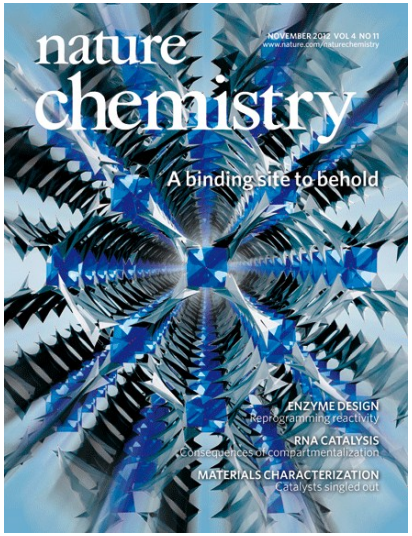


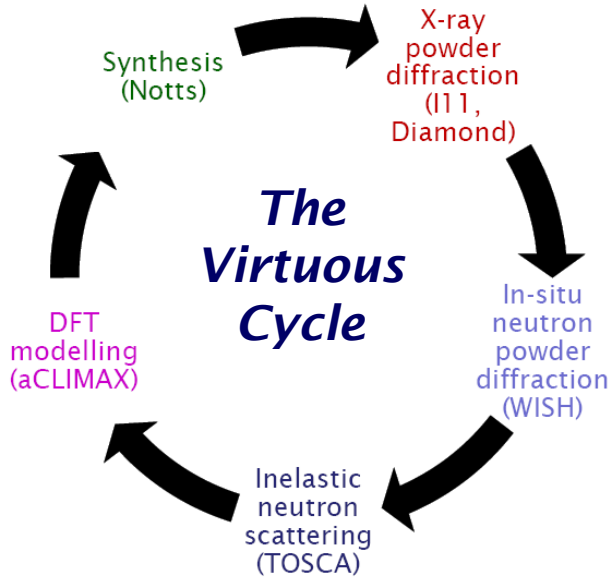
Selective Greenhouse-gas Sequestration on *TOSCA*



Selectivity and direct visualization of carbon dioxide and sulfur dioxide in a decorated porous host

Sihai Yang[1]*, Junliang Sun[2], Anibal J. Ramirez-Cuesta[3], Samantha K. Callear[3], William I. F. David[3,4], Daniel P. Anderson[1], Ruth Newby[1], Alexander J. Blake[1], Julia E. Parker[5], Chiu C. Tang[5] and Martin Schröder[1]*



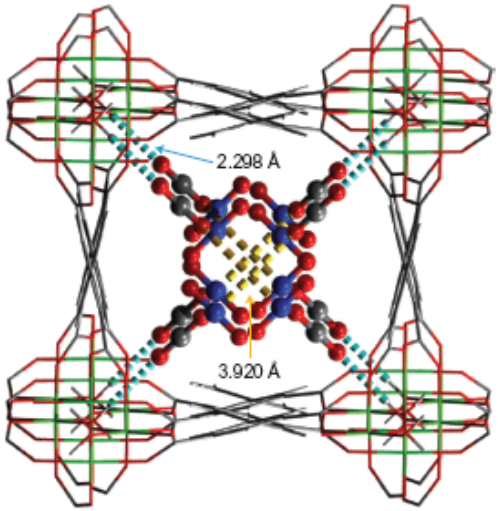


- Neutrons, X-rays, and modelling required.
- Selective binding of CO_2 and SO_2 to NOTT-300 hydroxyl groups.

NOTT-300 framework material

Amine-free

Environmentally friendly

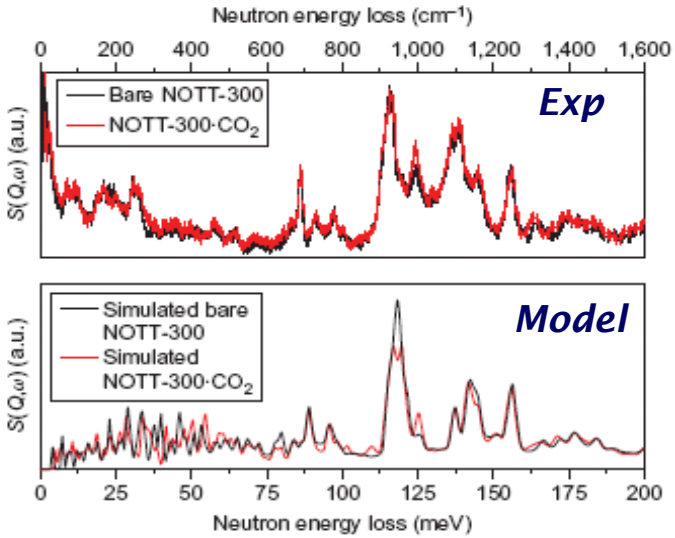


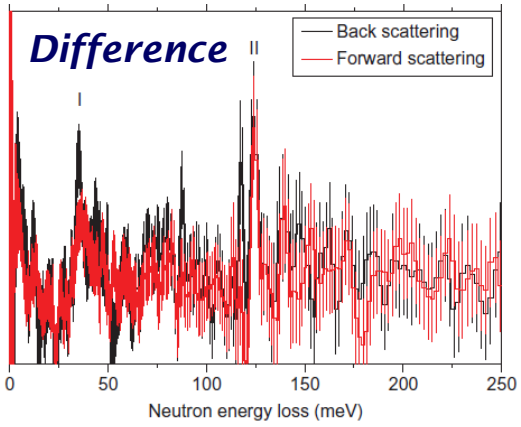
The University of Nottingham

Science & Technology Facilities Council ISIS

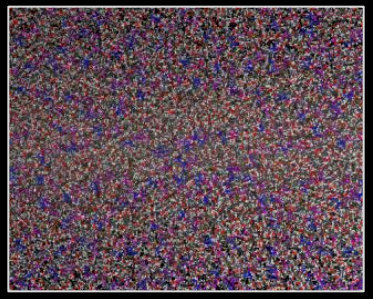
diamond

Neutron Spectroscopy: CO_2





CLEAN POWER: MATERIALS ISSUES



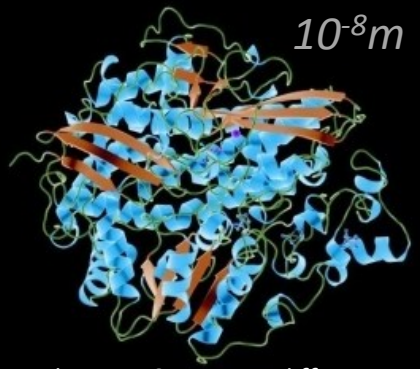
atomic understanding

10^{-10}m

X-ray & neutron diffraction
EXAFS
Inelastic neutron & X-ray scattering
Computational modelling (DFT / MD)

Macromolecules
(hydrogenase)

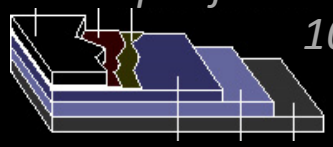
10^{-8}m



Small-angle X-ray & neutron diffraction
X-ray & neutron reflectometry
Protein crystallography

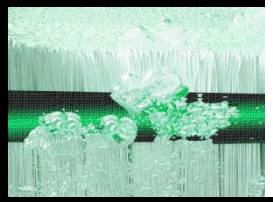
photovoltaics
p-n junctions

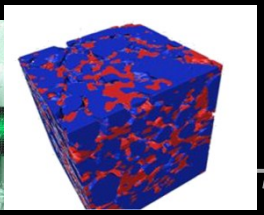
10^{-6}m



First principles device modelling
X-ray & neutron reflectometry

fuel cells 10^{-4}m



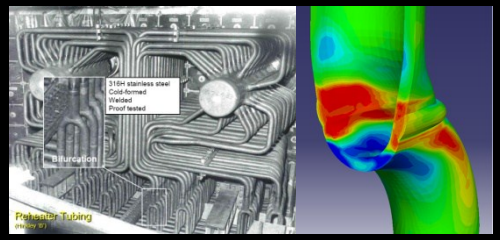


X-ray tomography
Device design

High energy X-ray diffraction
Neutron & X-ray residual stress analysis

1m

Reheater tubing failure



Nuclear industry

Li batteries



10^{-2}m

Studies of fabrication processes

Novel fuel sources for cars

CO_2 sequestration

Hydrogen storage

Photovoltaics

Electrolytes

Fission

Catalysis

Novel fuel cells

High performance batteries

Lowering exhaust emissions

Advances in energy conversion

Lower emission levels of pollutants

Significant improvements in energy storage

New environmentally friendly materials by rational design

High temperature gas flow through cell

- The schematic diagram of the flow-through gas cell
- (1) oxygen and temperature sensor
- (2) gas inlet
- (3) gas outlet
- (4) heater element
- (5) heat shielding
- (6) quartz sample holder
- (7) sample
- (8) quartz frit
- (9) thermocouple



Haynes R, Norberg ST, Eriksson SG, Chowdhury MAH, Goodway CM, Howells GD, Kirichek O, Hull S
Journal of Physics: Conference Series 251:012090;
doi:10.1088/1742-6596/251/1/012090 2010

Catalyst cells



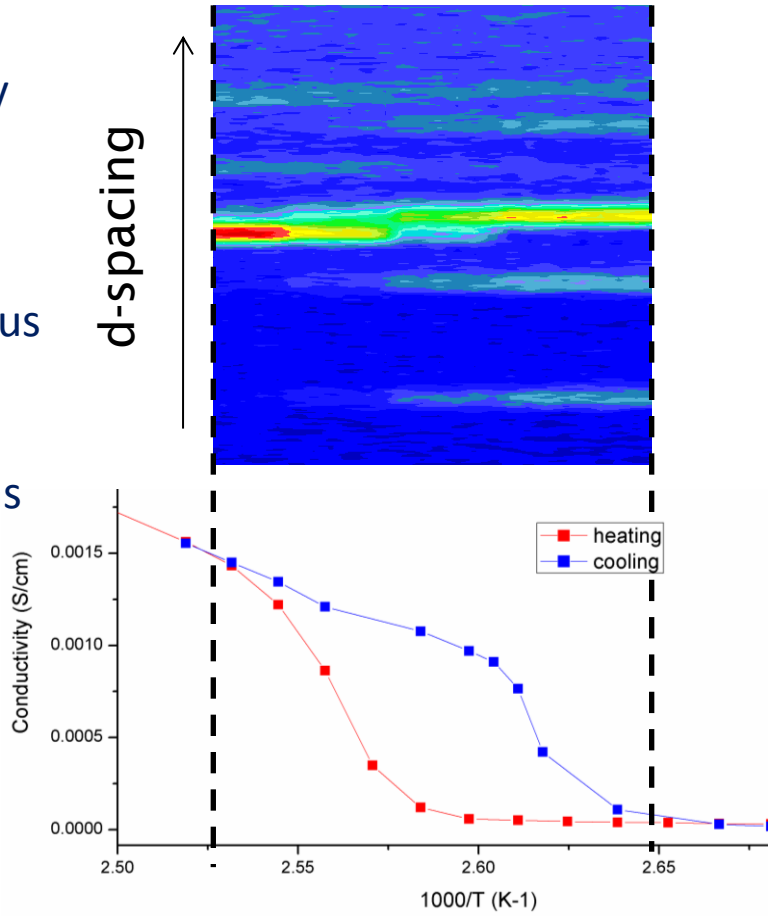
- (a) high temperature (> 600 K), flow-through, Swagelok™ sealed stainless steel cell
- (b) high temperature gold wire sealed Zircaloy™ cell and (c) low volume
- (d) high volume O-ring sealed aluminium cells for batch reactions
- (f) aluminium cell for off-line prepared samples
- (g) low temperature (323 K <) indium wire sealed aluminium cell
- (h) flow-through, Conflat™ sealed stainless steel cell for use on MARI at ISIS.

In-situ ionic conductivity analysis

- Simultaneous neutron diffraction and ionic conductivity measurements have been carried out at the ISIS facility
- Researchers from ISIS and Heriot Watt University have developed sample environment that allows simultaneous measurements of ionic mobility and structure
- Using the POLARIS neutron diffractometer, the team has been able to study lithium and proton conductivity in potential battery and proton conductor materials



Ionic mobility and structure sample environment apparatus



Typical ionic conductivity (lower) and neutron diffraction data collected simultaneously on the POLARIS diffractometer

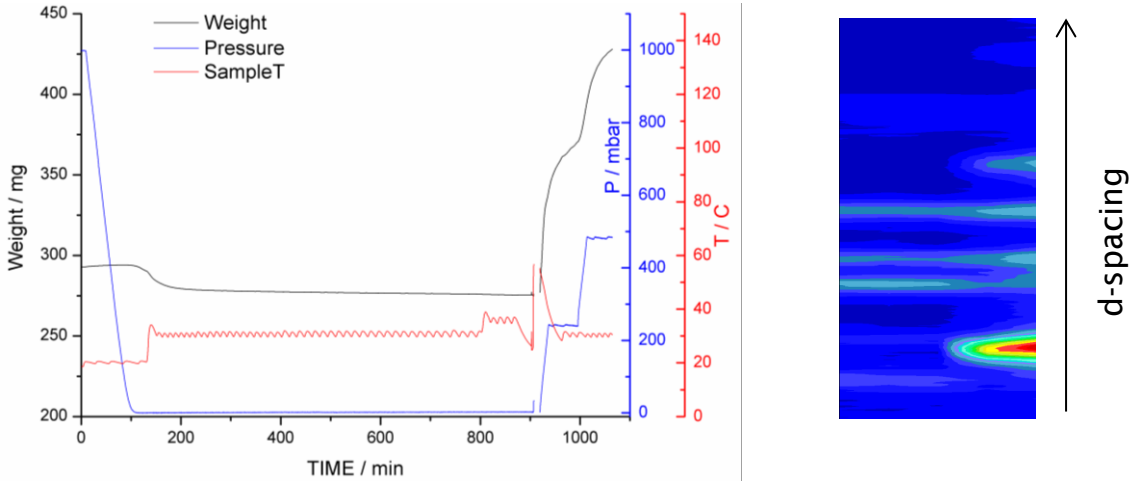
In-situ gravimetric and structural characterisation

- Scientists from the University of Oxford and ISIS have developed sample environment to simultaneously study the structure and thermogravimetric properties of hydrogen storage materials – the intelligent gravimetric analysis apparatus for neutrons, IGA^n

- The apparatus allows controlled gas, temperature (to 500^{o}C) and pressure (20bar) environments to be used to investigate gas uptake, desorption and cycling in hydrogen storage materials on the HRPD, WISH and GEM neutron diffractometers at ISIS

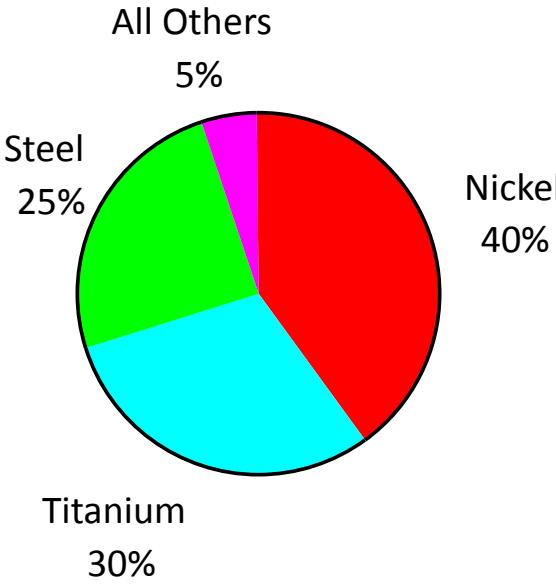


The IGA^n apparatus

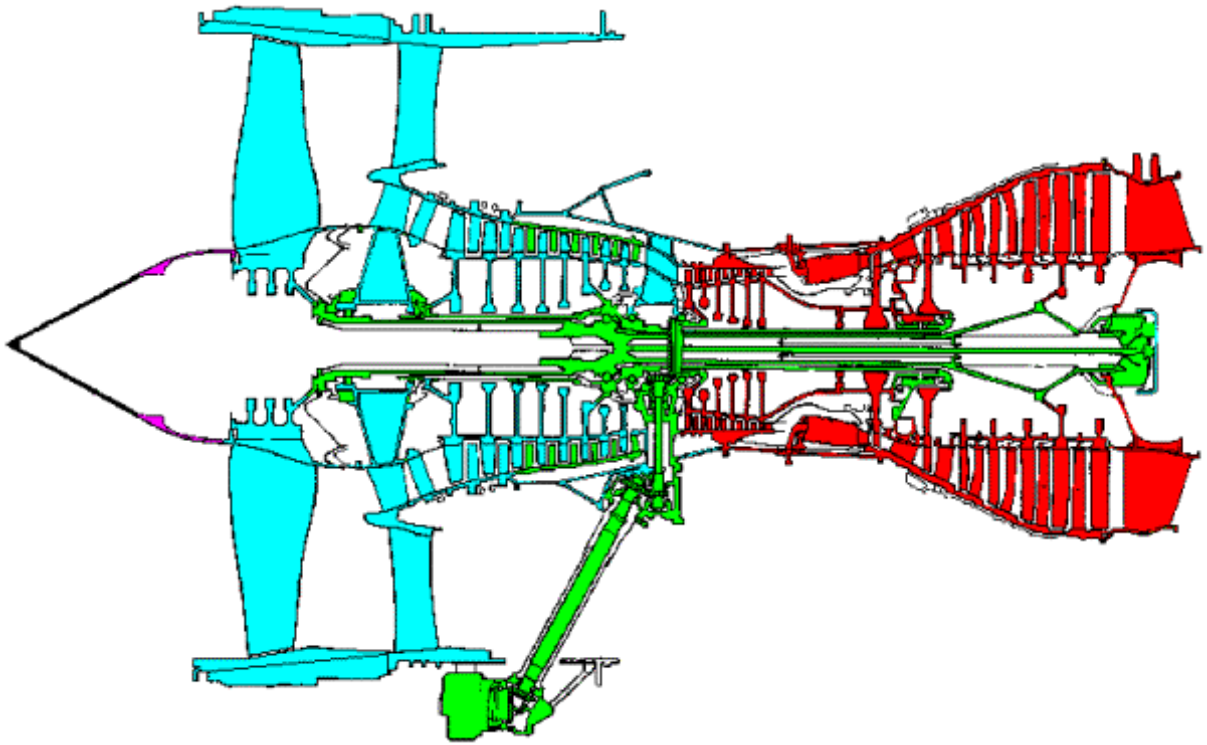


Sample thermogravimetric (left) and diffraction (right) data collected on the GEM neutron diffractometer using the IGA^n

Materials are a limiting technolog



- The efficiency of the engine is governed by the maximum pressure and temperature achieved in the centre of the core



Material durability is driven by;

- **Properties**
- **Residual stress**
- **Applied stress**

Therefore two out of three may be changed significantly in the performance of the components

MANCHESTER 1824

ROLLS ROYCE

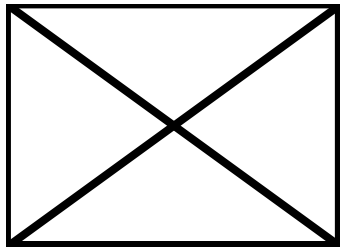
P. Whiters, M Preuss, et al.



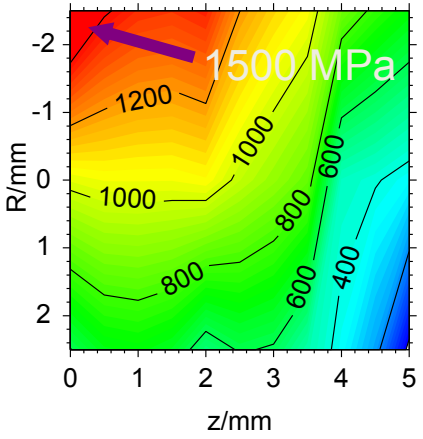
Rolls-Royce plc. Compressor rotor factory (CRF)



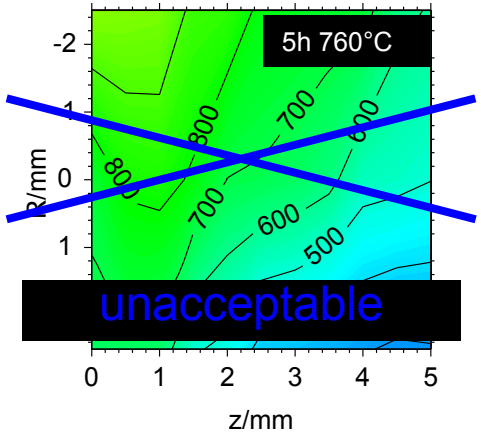
Prototype welded ring



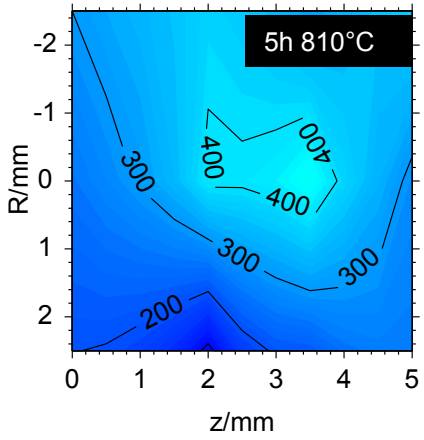
As welded



Conventional PWHT



Modified PWHT





Turski *et al* (2010).

- Magnesium is 30% lighter than aluminium.

  Mg alloys are important for aerospace and automotive industries to help reduce emissions.

- To be an economically viable alternative to aluminium, it must be mass produced.

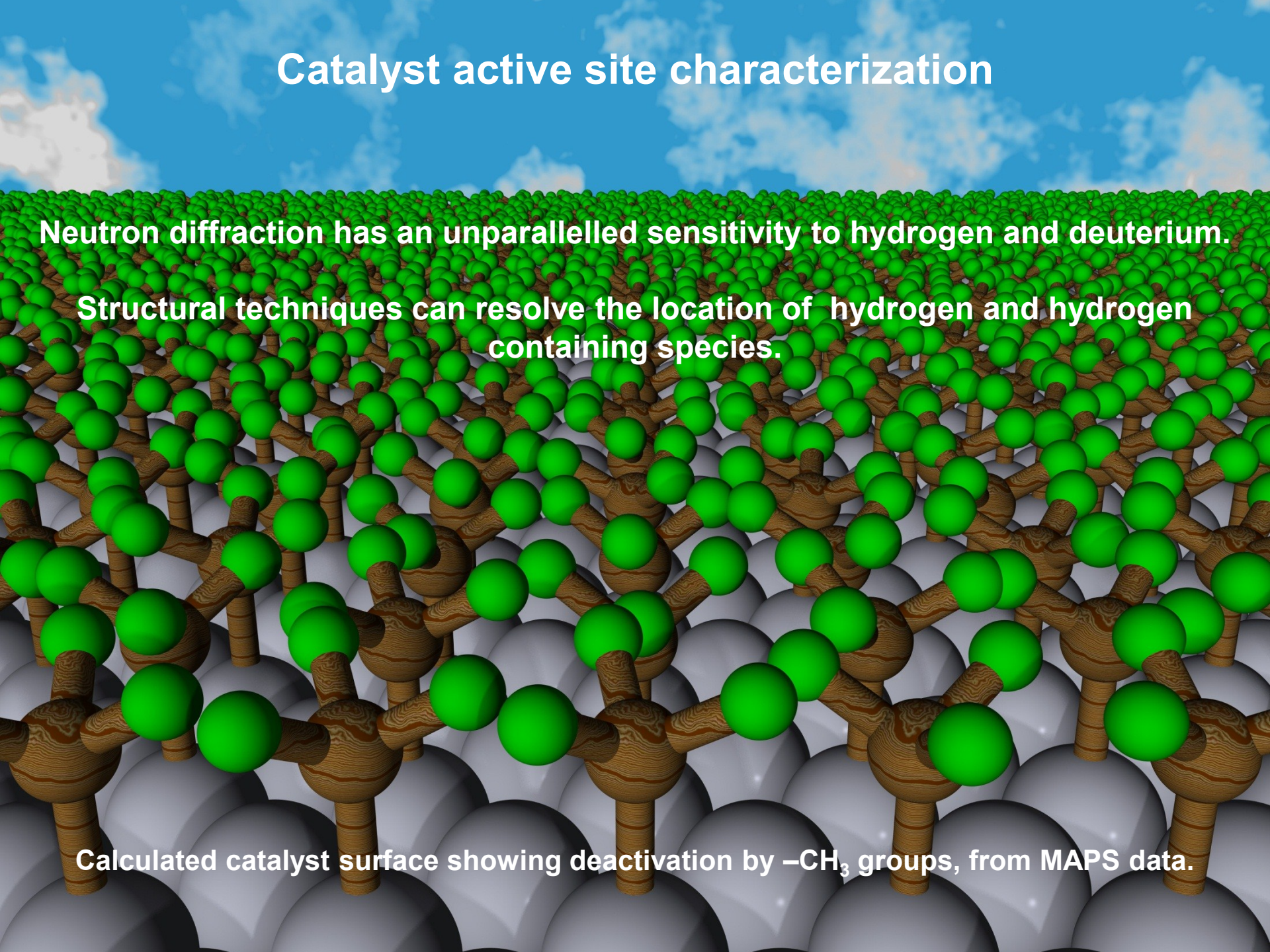
- Problem of producing large slabs due to cracking during casting.

- ENGIN-X used to map residual stress in large magnesium alloy slabs and identify regions prone to cracking.

Catalyst active site characterization

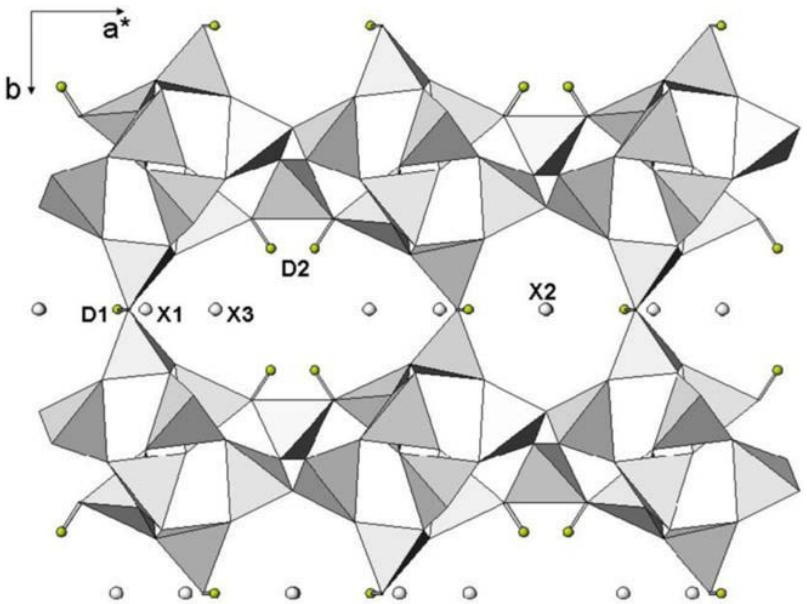
Neutron diffraction has an unparallelled sensitivity to hydrogen and deuterium.

Structural techniques can resolve the location of hydrogen and hydrogen containing species.



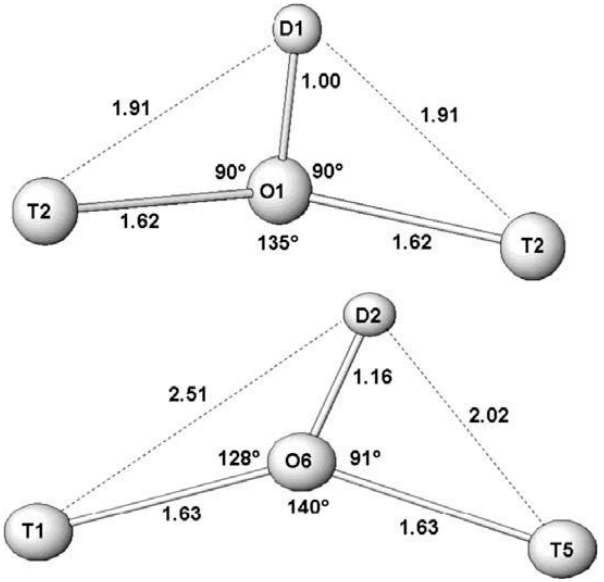
Calculated catalyst surface showing deactivation by $-CH_3$ groups, from MAPS data.

Active site position, geometry and proton mobility in acidic zeolites



Brønstead acid (D) and water molecule (X) sites.

Neutron diffraction can identify the Brønstead acid (D) and water molecule (X) sites and the geometry of the active sites



Geometry of the active sites

Permitting the proton mobility and the activity of the catalyst to be tracked.

Microporous and Mesoporous Materials **123** (2009) 15–20

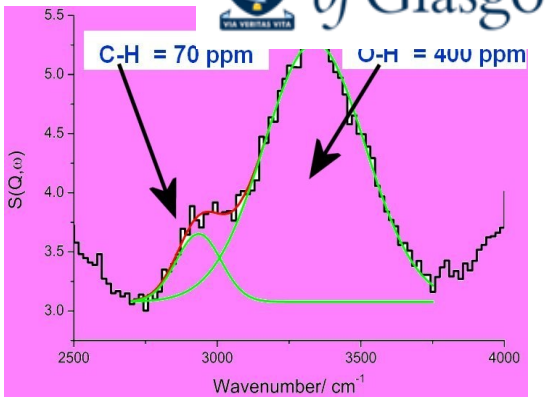
Dry reforming of methane: a use for CO_2?

KEELE UNIVERSITY

University of Glasgow



A methane reforming plant

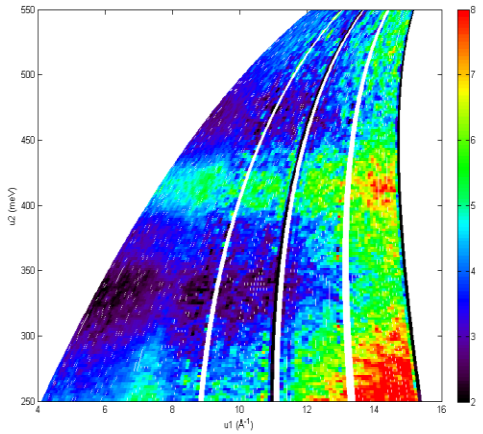


Data from the MAPS neutron spectrometer at ISIS identifying C-H and O-H stretches

- Industrially, hydrogen is produced by steam reforming of methane: $CH_4 + H_2O \rightarrow CO + 3H_2$
  An alternative route is to use CO_2 as the oxidant:
  $CH_4 + CO_2 \rightarrow 2\ CO + 2H_2$

- The process requires a $Ni(20\%)/Al_2O_3$ catalyst, which deactivates by carbon deposition

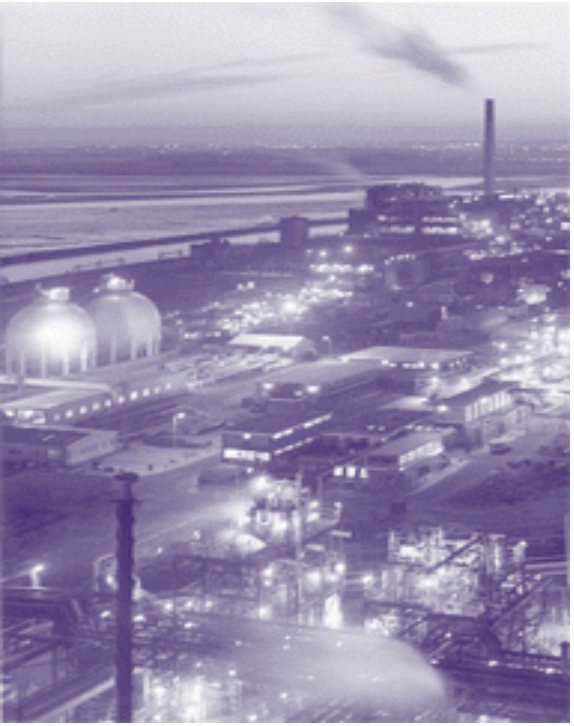
- Scientists at ISIS, University of Keele and University of Glasgow have used inelastic neutron scattering to characterise and quantify adsorbed hydrocarbon and hydroxyls determining that most of the CO_2 is converted to valuable CO and that the catalyst is very efficient at cycling hydrogen but not carbon



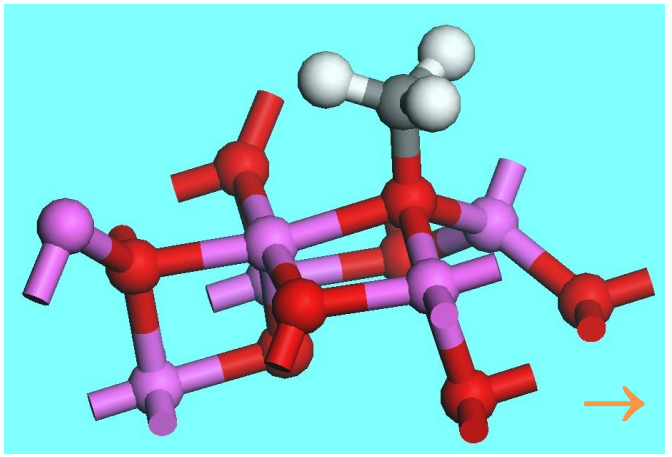


Quantification of surface species present on a nickel/alumina methane reforming catalyst
I. P. Silverwood, C. D. Frost, S. F. Parker, D. Lennon *et al* **12** 3102–3107 (2010)

Methyl chloride synthesis: a major process – 120000 tonnes per year at Runcorn



$CH_3OH + HCl \rightarrow$



$\rightarrow CH_3Cl$

Also: **$2\ CH_3OH \rightarrow CH_3OCH_3$** unwanted by-product

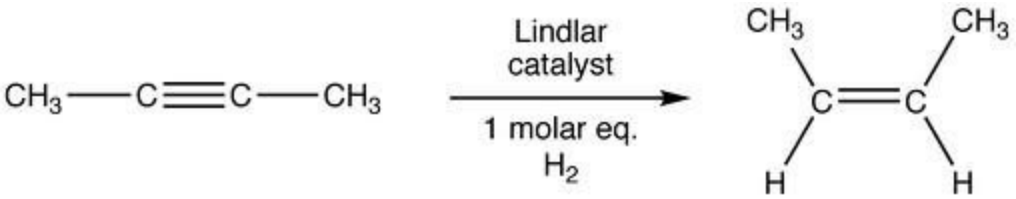
Able to modify catalyst so as to reduce amount of by-product

Cost saving of £4000000 and less CO_2

Catalysis for Vitamin-A Synthesis

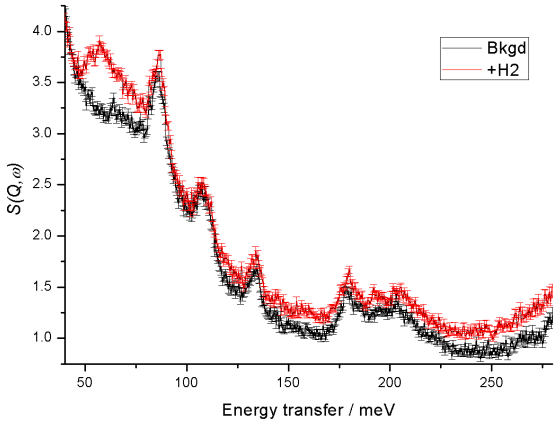
The Lindlar catalyst:

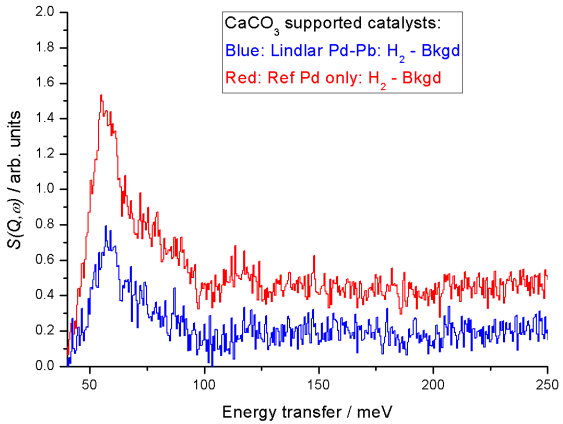
- Selective hydrogenation of C-C triple bonds to double bonds.
- No unwanted formation of C-C single bonds.
- Key step in the synthesis of vitamin A.





Neutrons: identification and quantification of surface species





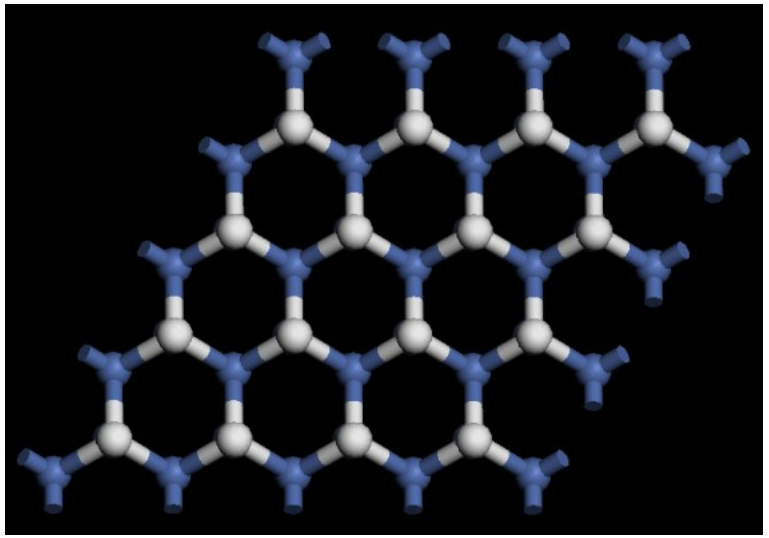
2.2x as much PdH in $Pd/CaCO_3$ than Lindlar

"The results generated by ISIS provided us with the missing piece of the jigsaw. We now know precisely how the Lindlar catalyst behaves and why it is so effective at preventing alkane production."

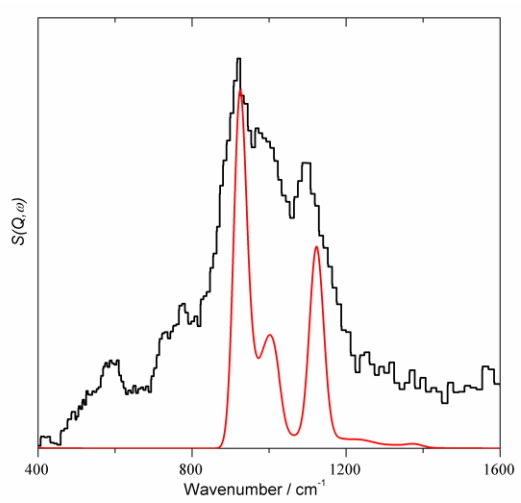
Dr Peter Albers -- AQura GmbH

PW Albers et al., *J. Phys. Chem. C*, 115 (2011) 24485.

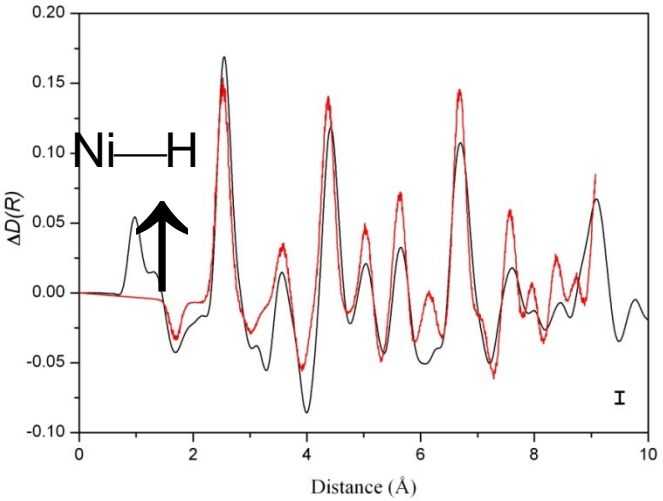
Theory, structure and spectroscopy combine to define hydrogen on Raney nickel



Theory – validation



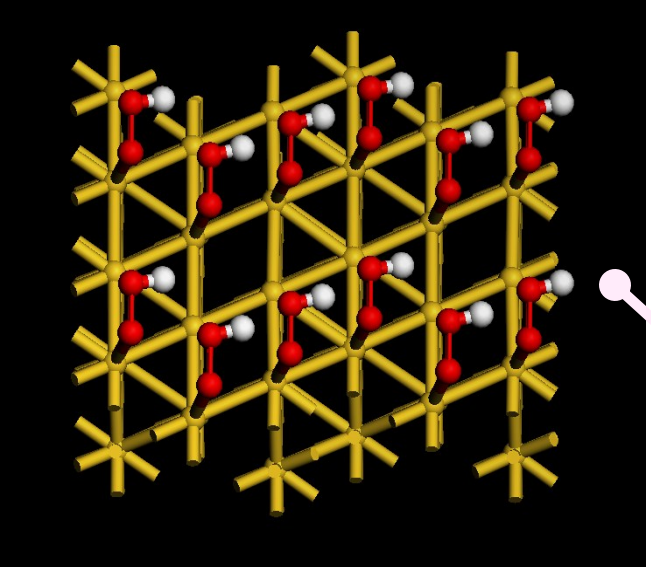
Spectroscopy – adsorption site



Structure – Ni-H bond distance

Au

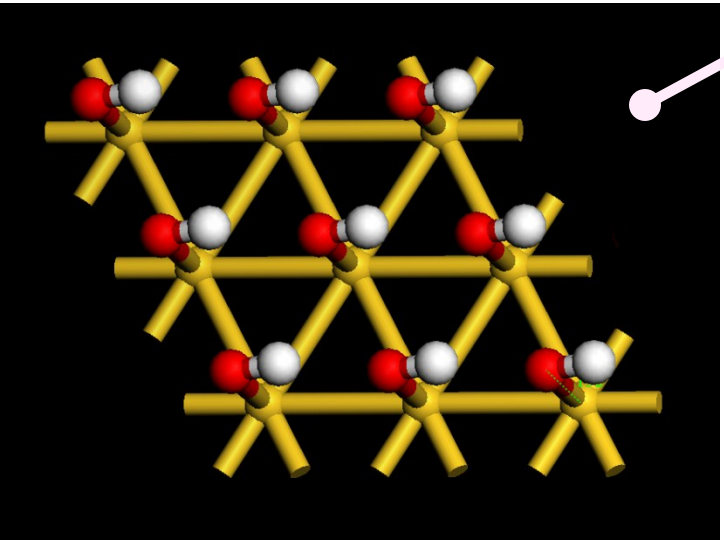
Au(1%)/CeO_2 most active catalyst for H_2O_2 synthesis.

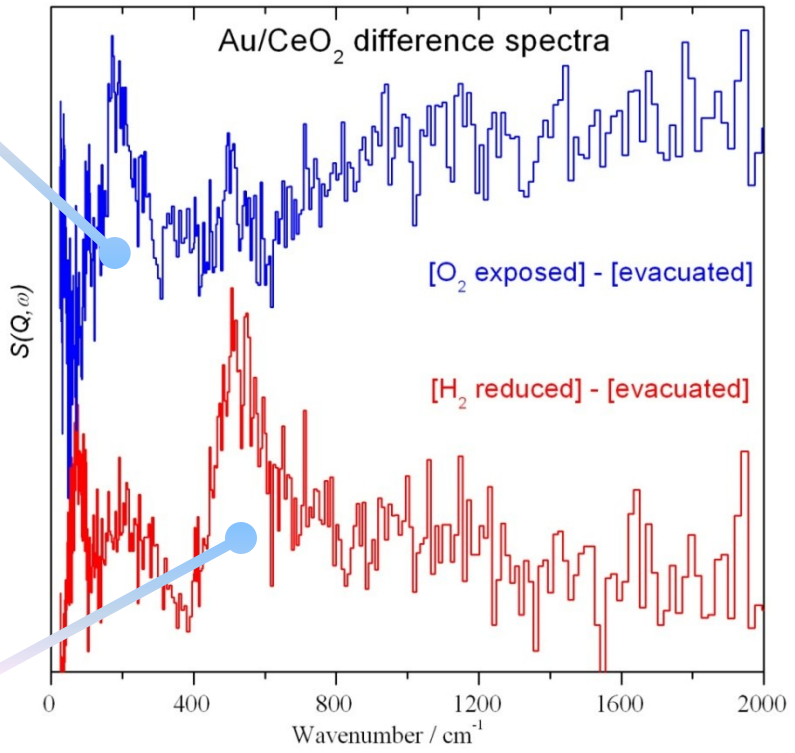


Hydroperoxide

↑

Hydroxyl

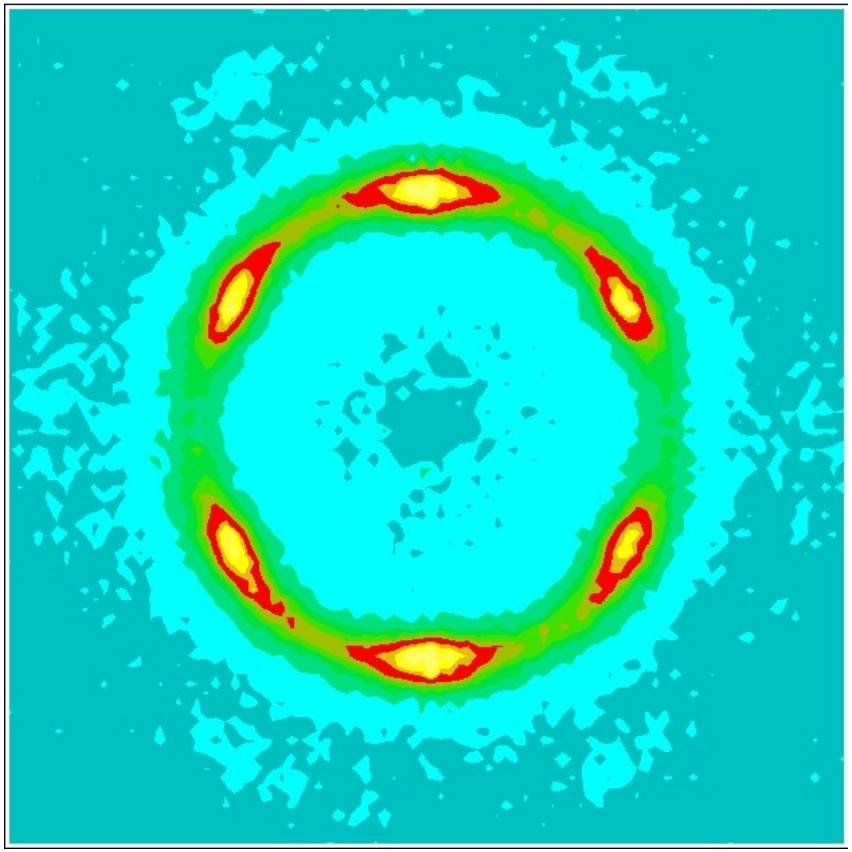




Au(1%)/CeO_2 dosed with H_2 then reacted with O_2.

Small Angle Neutron Scattering (SANS)

Investigate the internal microstructure and in homogeneities over micro- to nanometre scale range.

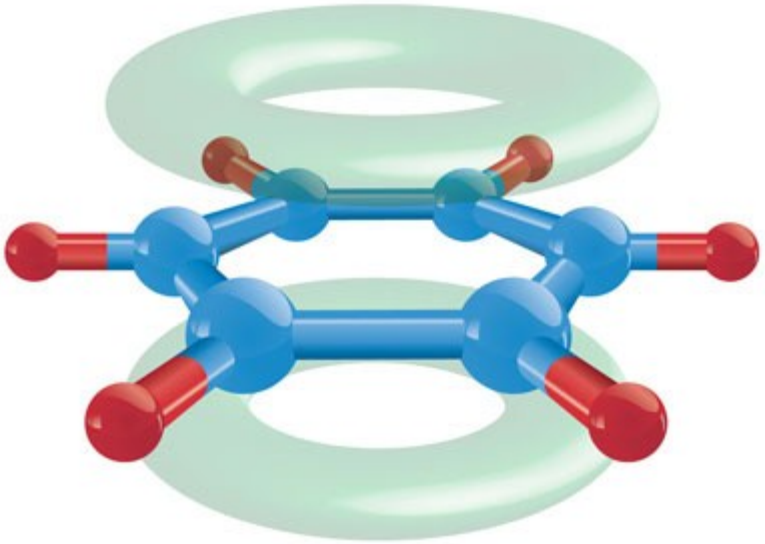


SANS Image

SANS can also provide information on the size, shape and orientation of some component of the sample

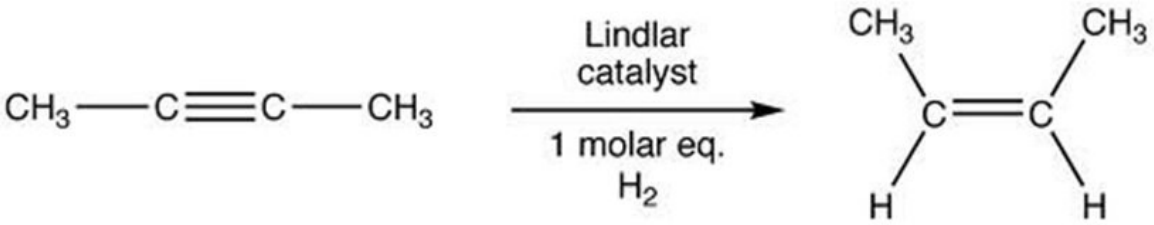
Molecular and liquid structure (Sandals)

Recent work at ISIS has determined the packing regime for liquid benzene using the Sandals diffractometer



Small angle neutron diffraction can also be used to determine the packing and structure of molecular liquids

Determining catalyst mechanisms



- The Lindlar catalyst is used for selective hydrogenation of carbon-carbon triple bonds to double bonds, without the unwanted formation of carbon-carbon single bonds, which is a key step in vitamin A synthesis

- Researchers from ISIS, Evonik Industries and Aqura Analytical Solutions utilised neutron scattering on the MAPS spectrometer to identify the catalytic mechanism



THE JOURNAL OF PHYSICAL CHEMISTRY C

Characterization of β-Palladium Hydride Formation in the Lindlar Catalyst and in Carbon-Supported Palladium

P.W. Albers, K. Möbus, C.D. Frost and S.F. Parker **115** 24485-24493 (2011)



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Matthias Gutmann	(STFC / ISIS)
Steve Hull	(STFC / ISIS)



Neutrons and muons

providing a unique view of the materials world



Thank you for your attention.