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Highlights from Faraday Discussion on Designing Nanoparticle Systems for Catalysis, London, UK, May 2018

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The 2018 Faraday Discussion on “Designing Nanoparticle Systems for Catalysis” brought together leading scientists to discuss the current state-of-the-art in the fields of computational chemistry, characterization techniques, and nanomaterial synthesis, and to debate the challenges and opportunities going forward for rational catalyst design. The meeting was a vivid discussion of how the communities accumulated knowledge and innovativity can be combined to have a stronger scientific impact. In the following, we provide an overview of the meeting structure, including plenaries, papers, discussion points and breakout sessions, and we hope to show, to the wider scientific community, that there is great value in continued international discussion and scientific collaboration in these fields.

Introduction

When attending a Faraday Discussion meeting, one immediately gets a sense of scientific continuation. Following a tradition established over 100 years ago, in 1907, with the first Faraday Discussion on “Osmotic Pressure”, [DOI: 10.1039/TF9070300012] the meeting symposiums have a distinctive format that makes them a unique experience amongst all other scientific dissemination forms. Indeed, the scientific papers presented in these events are provided in advance for all the attendees to read; then, during the meeting, the paper’s authors have the opportunity to briefly present their manuscripts within 5 minutes, followed by an extensive discussion of the work including impacts and future directions. This special format has the great advantage that it provides a broad overview on specific topics, allowing a direct critical analysis by the wider international scientific community.

There could have been no better place to host this 2018 discussion, about the “Designing of Nanoparticle systems for Catalysis”, than at Burlington House in London, which is the home of the Royal Society of Chemistry (RSC). Surrounded by the book-filled shelves of the RSC Library, an international representation of over 120 delegates convened on the 16th May, all eager to exchange opinions and visions on how to design and engineer structures for selective and efficient chemical synthesis.

Fittingly, the event commenced with recognition that the 2018 Faraday Lectureship Prize was awarded from the RSC to Prof Graham Hutchings, the chairperson of the event. This prize is awarded every two years for exceptional contributions to

physical science, for which Prof Hutchings is a worthy recipient.¹ In his subsequent introductory speech, Prof Hutchings introduced the three main themes of the meeting: the control of nanoparticles synthesis, the challenges of characterization, and the use of theory as a guide in our search for novel nanoparticle-based catalysts. Therein, the meeting was declared open.

Figure 1. Façade of Burlington House, Piccadilly, London; home of the Royal Society of Chemistry.

Opening Lecture



The introductory lecture was given by **Prof Bruce Gates**, from the University of California, Davis (USA), who is a world-leading figure in the design of supported metal clusters for catalysis and also author of excellent catalysis textbooks.² In his talk, Prof Gates shared his vision and strategies on how to attain the needed molecular foundation for application-oriented synthesis of supported clusters and nanoparticles (NPs), giving

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several detailed examples that showcase when the goal of design could be achieved. He introduced the concept of nuclearity of supported catalysts and identified two extreme cases representing different foundations of chemical science: precisely synthesized single-site metal atoms, and larger nanoparticles (NPs). The reactivity of atomically dispersed metal species is well described by organometallic chemistry. On the other hand, for larger NPs, surface dynamics and restructuring typical of the corresponding bulk systems are to be expected and thus these are normally considered using surface science approaches. Clusters and small NPs exist in a large variety of shapes and sizes between these two delimiting cases. The chemical interactions between the nanostructures and the support onto which they are immobilized provide further opportunities to fine-tune the catalytic properties; moreover, both ligands on the surface of the metal as well as on the support itself, can also play an important role in catalysis. In contrast to most of the supported NPs obtained by wet impregnation followed by thermal annealing, almost always inhomogeneous in shapes and sizes, well-defined few-atoms metal clusters can be obtained via direct adsorption of ligated molecular metal clusters or deposition of size-selected metal clusters from the gas-phase onto an oxide support.³ Adsorption-based synthetic methodologies enable a precise control of the system's structural properties in the initial state, and also meaningful monitoring of the structural modifications at the molecular scale, thus providing model systems with which one can develop a fundamental understanding of catalytic phenomena. Indeed, Prof Gates stressed the importance of starting from a well-defined system and the use of several characterization techniques to study structural dynamics of clusters under catalytic reaction conditions (i.e., *in operando*).

Prof Gates makes extensive use of state-of-the-art characterization techniques, including high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM). He acknowledged that the foundations of the science of clusters and single atoms on supports would not be nearly as strong as they are now without the technological advancement of the modern transmission electron microscope (TEM). Due to atomic scale resolution, and a high sensitivity to atomic number contrast, HAADF-STEM allows the direct visualization of heavy metal atoms forming clusters or the NPs on light-atom supports in a 2-dimensional projected image. More recent advanced image processing and complementary spectroscopy allows obtaining a 3-dimensional model of the analysed object and sometimes even the structure of the metal-support interface. One of the key questions addressed during his talk was the effect of nuclearity on the catalytic activity. As a first example, Prof Gates discussed atomically dispersed Au supported on CeO₂ for carbon monoxide oxidation.⁴ By means of *operando* X-ray absorption fine structure spectroscopy, he showed that a sharp increase in the conversion coincides with the formation of Au-Au dimers from an initial Au(CH₃)₂(acac) complex, and it proceeds to the steady state, in which the coordination number of Au increase slowly up to gold nanoclusters. The next example was the selective hydrogenation of butadiene using isolated rhodium dimer complexes, which showed the contrast in

catalytic properties between isolated rhodium atoms and extremely small rhodium clusters supported on zeolite H-Y. Here, Rh(C₂H₄)₂ complexes catalyse both the dimerization and hydrogenation of ethene, and a controlled thermal treatment to produce rhodium clusters of only a few atoms boosts the activity for hydrogenation, eliminating the dimerization.⁵ Another interesting study that exemplifies the high precision attainable by in-situ methodologies for chemical speciation is the case of Ir tetramers with bulky calixarene phosphine ligands, used for ethylene hydrogenation, where it was possible to identify that apical Ir atoms in Ir₄ tetrahedra catalyse the hydrogenation reaction whereas the basal Ir atoms are inactive.⁶

The last point made by Prof Gates was on the catalysts' stability issue under reaction conditions. Synthetic strategies to encapsulate NPs in microporous materials, such as zeolites or metal organic frameworks, are being explored to improve stability against sintering and coking resistance. As concluding remarks, Prof Gates emphasized how *In situ* spectroscopy and transmission electron microscopy are formidable techniques to produce fundamental understanding; however, in view of generating further knowledge, site precision synthesis is a pre-requisite for establishing robust structure-function correlations.

Session 1: Theory as a driving force to understand reactions on nanoparticles.

The discussions themselves began with six papers grouped into two sequential sessions, with a wide span of discussion topics focusing on the use of computational modelling in catalytic applications. **Prof Rutger van Santen** (Eindhoven University of Technology, The Netherlands) presented his work first, which had the broad title of "*The challenge of catalyst prediction*", where he emphasised his belief that current computational approaches need to accurately predict both transient initiation as well as deactivation processes on (and within) catalysts. [DOI: 10.1039/c7fd00208d] Quantitative data could then be fed into microkinetic models to provide a more complete description of catalytic mechanisms. The provision of experimentally comparable observables, rather than qualitative trends, is a very topical issue in the field of computational catalysis; a specific mention in the discussion was made to the recent work of Phillippe Sautet and the consideration of transient catalyst structures on the observable rate constants and reaction turnovers.⁷ There was an inevitable suggestion of the use of machine learning to facilitate insight, given that vast amounts of data could need analysing in these approaches. Limitations were noted in the ability of computational approaches to produce enough accurate data to warrant such an approach in catalysis. Indeed, these discussion points became a persistent theme throughout all theory-led discussions.

In the first session, there was also a presentation from **Prof Roy Johnston** (University of Birmingham, UK), entitled "*Modelling free and oxide-supported nanoalloy catalysts: comparison of bulk-immiscible Pd-Ir and Au-Rh systems and influence of a TiO₂ support*", and from **Dr David Willcock** (Cardiff

University, UK), entitled "*Structural behaviour of copper chloride catalysts during the chlorination of CO to phosgene*". The work of Johnston *et al.* focuses on the stability of differing chemical configurations for bimetallic nanoparticles, using a fixed nanoparticle morphology cut from the bulk FCC crystal, and supported on the rutile (110) surface of TiO₂. [DOI: 10.1039/c7fd00213k] In both systems studied (Pd-Ir and Au-Rh), strongest surface interactions were observed when the non-noble metal interacted with the support surface, commensurate with the monometallic results, thus paving a way to introduce support-induced elemental segregation in the nanoparticles, and providing a rationale towards improving nanoparticles anchoring. The discussion debated the value of limiting the models to those outlined, exploring whether the bulk crystal fragment is representative at these low nuclearities, as surface wetting by the nanoparticles may be expected; detailed discussion of charge distribution at interface was also considered, and how this will affect reactivity. In the latter case, it was noted that other substrates preferred in catalytic applications, such as alumina or haematite, are much less ordered and so expanding the work to make it more relevant to catalytic applications remains challenging. In contrast, the work of Willock *et al.* includes comparison between experiment and theory for the reactivity of attapulgite-supported Cu(II)Cl₂. [DOI: 10.1039/c8fd00005k] In the experiment, CO exposure leads to oxidation of the reagent to CO₂ for the as-received catalyst; however, Cl pre-treatment leads to synthesis of phosgene. This reactivity is linked back to the formation of surface defects during the Cl pre-treatment, with density functional theory (DFT) simulations corroborating XANES data to show that this could lead to Cl- surface defects. Such defects result in Cu(I) and Cu(II) ions at the surface, with DFT showing strong CO interaction with the former allowing formation of the COCl₂ product. Due to the more applied nature of this work, compared to that of Johnston *et al.*, the discussion in-turn moved towards the role of free energies and entropy in determining rates; furthermore, the periodic nature of the studied catalyst, rather than a discrete nanoparticle, left questions about the role of supports and/or promoters to improving the catalytic reactivity.

After a short coffee break, with much intense discussion already about the advantages and drawbacks of computational approaches, the session reconvened with more computational-focused investigations. **Prof Nora de Leeuw** (Cardiff University, UK) introduced a comparative DFT study of small Ni nanoclusters on ZrO₂ and YSZ (111) surfaces. [DOI: 10.1039/c7fd00217c] On both supports, the nanoparticles formed pyramidal structures rather than wetting the surface, with charge transfer returning as a topic of debate for the support-nanoparticle interaction. The Ni atoms interact strongest with the electronegative O in the support, forcing geometric changes in YSZ. These support-interacting atoms are typically positively charged, whereas Ni atoms furthest from the support become slightly negative; such subtle differences could easily affect reactivity. The use of kinetic Monte Carlo approaches leads to a conclusion that surface aggregation would occur under medium temperatures, with sintering

occurring independently of initial surface coverage. When the floor was opened, the debate here reverted to similar themes encountered for the work of Johnston *et al.* with the focus on the importance of realistic models of the support and also the reaction environments, particularly solvents, identified as areas for further work.

Perhaps one of the most of the widely debated papers of the day followed, when **Mr Wilke Dononelli** (Carl von Ossietzky Universitat Oldenburg, Germany) introduced his work on CO and O₂ adsorption on Group XI nanoparticles using both DFT and high-level coupled-cluster [CCSD(T)] approaches. [DOI: 10.1039/c7fd00225d] The work used exemplar models for the nanoparticles, containing 13- and 55-atom structures, and considered Au, Ag and Cu monometallic compositions. For CO adsorption the results of the 55-atoms system are similar to a high index (321) surface, whereas the differences are much greater for the 13-atom system (up to 0.6 eV for Cu). The authors postulate a naïve assumption that the PBE approach of DFT would lead to overbinding but QM/QM calculations, with CCSD(T) used for the adsorption site, give almost identical results. The dissociation barriers for O₂ were identified as being prohibitively high, thus showing that direct molecular reactions (Eley-Rideal) are more suitable for CO oxidation than the surface-mediated Langmuir-Hinshelwood type mechanisms.⁸ Inevitably, when the floor-opened for questions, there was much debate about the role of CCSD(T) in acting as a benchmarking guide to DFT. In particular, opinions were sought on how high-level theory could be used to improve or standardise empirical corrections to DFT, e.g. commonly used Hubbard or Grimme-type corrections. However, it is noted that cautionary comments were also raised: CCSD(T) cannot be assumed as a "silver bullet" that could solve all modelling problems, given the complex nature of ensuring accuracy with this higher-level approach.

Finally in this session, **Dr Arun Chutia** (University of Lincoln, UK) presented his work on "*The electronic properties of Au clusters on CeO₂ (110) surface with and without O-defects*". [DOI: 10.1039/c8fd00002f] This work returned to the topics of metal nanoparticles and their interaction with supporting materials, specifically focusing on Au atoms and dimers on a low-energy ceria surface. It was observed from DFT calculations that the charge state of the adsorbate can be strongly altered by the presence of O-defects in the ceria, varying between cationic and anionic forms, with density of states analysis used to validate observations. Specifically, Au⁺ exists in the absence of defects, with charge transfer to the Ce atom of the support, whereas adsorption over O vacancies results in Au⁻. Strong similarities to the work of Prof De Leeuw *et al.* were born in the post-presentation discussion, with emphasis on characterising the charge transfer effects and how this will alter the catalytic chemistry. For instance, alternative probe CO molecules were suggested, as these are responsive to charge transfer and can be linked to experimental spectroscopic techniques. Further discussion also covered the role of the nanoparticle-supporting ligands on the structure and surface-interaction of the nanoparticles. Although this topic was not covered in any of the

computational work presented, it is of key importance if the results are to be related to experiment.



Figure 2: After some excellent presentations and debate, discussions continued at the end of day 1 with the poster session.

To complete Day 1, then followed a series of “quick-fire” flash introductions to precede the evening’s poster presentation. 20 presenters were given just one minute and one slide to pitch their work to the audience, with a rapid turnover between presenters, leading to a mixture of presentation styles and details that only wetted the appetite for the subsequent session. Then, followed two hours of poster-mediated discussion, with over 30 posters presented. The debate was flowing and engaging, the attendees consumed by questions and discussions either of the day’s work or poster content. Even once the evening’s session had closed, the debate continued on to some of London’s other fine “meeting” establishments, though conclusions were drawn (or at least postponed) in time for everyone to get home and prepare for the following days discussions.

Session 2: The challenges of characterizing nanoparticulate catalysts

One of the big dreams that scientists in the field of catalysis share is the full understanding of the catalytic phenomenon at the molecular level. This search has intrigued chemists from the dawn of this science when it was realized that materials manifesting catalytic activity towards a reaction, remain also unaffected by the reaction itself unless they are deactivated.⁹ Nowadays, scientists are developing sophisticated spectroscopic and imaging methodologies for attaining the needed time and space resolutions to follow the structural dynamics taking place at the reactive interface during the

catalytic turn-over. Thus, it is timely that Session 2 is dedicated to the application of *in situ* methodologies to catalysis, with a critical assessment of capability and limitations.

With this perspective, the second day started with a session chaired by Prof Mike Bowker and a talk delivered by **Prof Carlo Lamberti** (University of Torino, Italy) on time-resolved *operando* studies of carbon supported Pd nanoparticles (NPs), under hydrogenation reactions, by X-ray diffraction and absorption [DOI: 10.1039/c7fd00211d]. In this work, by a combination of X-ray powder diffraction (XRPD), extended X-ray absorption fine structure (EXAFS), X-ray absorption near edge spectroscopy (XANES) and volumetric analysis in a wide range of sample temperatures and H₂ equilibrium pressures, the authors are able to identify the structure of these NPs under reaction condition as composed of an ordered core and a disordered shell. XRPD patterns reveal a direct structural-reactivity relationship during the ethylene hydrogenation reaction, where periodic oscillations of the lattice parameter of the crystalline core of the NPs correspond to oscillations in the mass fragment signal of C₂H₄ and C₂H₆ recorded simultaneously in the mass-spectrum. Advanced analysis of the Δ XANES spectra allows the detection of carbon-containing molecules adsorbed at the surface of the NPs. Finally, some insights into the catalysts deactivation mechanism were also provided where the local temperature and hydrogen concentrations drive the formation and disappearance of the β -phase and thus of the catalytic activity.

Following, **Dr Annette Trunschke** (Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany), discussed a paper focused on the investigation of structural dynamics of (Mn,Fe)O_x promoted Rh nanoparticles under hydrogenation of CO to higher alcohol. [DOI: 10.1039/c7fd00215g]. Dr. Trunschke started her talk by referring to the computational chemistry contribution from the group of Prof Norskov¹⁰ in which the authors failed to find a catalyst for the hydrogenation of CO to ethanol. This experimental work demonstrates that, on Rh catalysts, support and promoters (Fe, Mn) make this reaction possible. By applying a combination of integral techniques such as temperature-programmed reduction (TPR), X-ray photoelectron spectroscopy (XPS), X-ray absorption spectroscopy (XAS) and Fourier transform infrared (FTIR) spectroscopy together with local analysis by using high angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) and energy dispersive X-ray spectroscopy (EDX), the authors conclude that the active sites are associated with either a (Mn,Fe)O_x ($x < 0.25$) phase or species at the interface between Rh and its co-catalyst (Mn,Fe)O_x, whereas Rh⁰ is poisoned due to the strong adsorption of CO under the reaction conditions. In the conclusion, this contribution showed that it is indeed possible to break scaling relations by creating new interfaces of metal nanoparticles with a co-catalyst (support, promoters).

The last talk before the break was delivered by **Dr Michele Carosso** (University of Torino, Italy) who presented the work titled “Looking for the active hydrogen species in a 5 wt% Pt/C catalyst: a challenge for inelastic neutron scattering”. (DOI: 10.1039/c7fd00214a). Therein, by coupling H₂ adsorption

measurements with inelastic neutron scattering, the authors were able to determine the H speciation on both the metal and the carbon support with unprecedented structural detail, including the demonstration, for the first time, of molecular H₂ physisorbed on the metal surface, as well as the atomic H spillover from the metal to the carbon surface.

Topics of the discussion session included how to ascertain, from integral techniques, the correct NP structural model when presented with two equally valid chemical configuration models: e.g. discriminate between the ordered-core/disordered-shell structures from a broad NP size distribution, where the small NPs could account for the disordered part. Indeed, there was a general consensus from the audience on the importance of the application of complementary characterization techniques, with accessibility championed through the model of the Harwell Science and Innovation Campus in the UK. A more general discussion was characterized by an historical digression on the use of XAFS techniques from the EXAFS "boom" in the early 80s to nowadays, when XANES is gaining increasingly interest especially for diluted systems. This modern shift is enabled by the modern capability of theory to predict XANES spectra, with an outlook into the future in which machine-learning approaches can revolutionize the way to interpret XANES data.

Part B of this session was devoted to the study of catalytic systems based on Au nanoparticulate systems. **Dr Yaroslav Odarchenko** (University College London and Research Complex at Harwell, UK) opened the session by discussing his use of grazing incidence X-ray scattering *in operando* to study CO oxidation over a well-defined 2D-system composed of monodispersed gold nanoparticles periodically arranged on a single crystal SiO₂ substrate. [DOI: 10.1039/c8fd00007g] By using grazing angles, this intrinsically bulk technique is able to provide surface structural information. The authors show the peculiar modification of the Au NPs, which flatten due to the enhancement of the NPs' wetting area under reaction condition. The findings support a dual model of active sites located at the metal/support interface, in which the CO is activated at the Au metal site and the O₂ is activated at the interface with the support.

Following, the talk delivered by **Prof Valerii I. Bukhtiyarov** (Boreskov Institute of Catalysis and Novosibirsk State University, Russia) was the only example in this conference of the application of *in situ* surface sensitive X-ray spectroscopy to study CO oxidation over bimetallic Pd-Au/HOPG systems. [DOI:10.1039/c7fd00219j] By means of near ambient pressure XPS, in combination with the on-line detection of the gases by means of mass spectrometry, the authors were able to capture the dynamic segregation of Pd towards the surface under reactive mixture and at temperature below the reaction temperature. The surface segregation was associated to the strong chemisorption of CO on Pd, whereas the reversible segregation of Au to the NPs surface and the formation of Pd-Au alloys were observed under CO oxidation regime. The next talk of the session was given by **Prof R. A. Nome** (Institute of Chemistry, Brazil), where the authors used hollow Ag-Au NPs of well-defined size and composition synthesized by galvanic

replacement method and characterized them by means of UV-Vis and ultrafast spectroscopy, with the goal of contributing new insights into composition dependent catalytic activity. [DOI: 10.1039/c7fd00220c] Therein, the authors propose an original approach, which ultimately could allow to precisely determining the surface composition of bimetallic NPs under reaction condition. Particularly, the authors study the fundamental molecular motion of NPs by means of ultrafast time-resolved spectroscopy, which depends on their structural composition. They validate this approach for the specific case of the Ag-Au NPs, with Pump-Probe Spectroscopy used to extract fundamental electron-phonon coupling time constants as a function of the nanoparticle composition. The authors also performed all-atom molecular dynamics simulation of model hollow Ag-Au core-shell NPs to characterize the stability and equilibrium structure, and to obtain an atomic view of the NPs surface composition. The basic atomistic and electron-lattice dynamics of core-shell Ag-Au NPs aid the mechanistic understanding and performance optimization of Au-Ag NPs catalysts.

The last talk of the session was given by **Mr A. L. Bugaev** (University of Torino, Italy), who, similarly to the first talk, used a combination of *in situ* XRPD and XAS to investigate the synthesis of Pd nanoparticles inside UiO-67 for ethylene hydrogenation. [DOI: 10.1039/c7fd00224f] The authors were able to prove that the Pd(II) species of the precursor are initially coordinated to the N site of the ring but lose their coordination with the framework upon hydrogenation, instead coalescing to form NPs entrapped in the cage of the MOF structure. The entrapment of the NPs within the cage of the UiO-67 enabled a much higher stability against coking.

The last part of this session was dedicated to capturing the catalytic process by microscopy techniques. After another lively lunch, the session was opened by **Prof Haio-Joachim Freund** (Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany) who delivered a clear and important message that, in order to isolate the effect of the various components of a catalyst, *in situ* characterization should focus on a systematic approach, which looks at systems with increasing level of complexity to finally approach the real system. [DOI: 10.1039/c7fd00209b] Prof Freund elaborated on two systems: a) the design of a model system for the Phillips catalyst (Cr/SiO₂) for ethylene polymerization and b) Au NPs on MgO(100)/Ag(100). For the first example, after many years of attempt, it is now possible to investigate mechanistic aspects of this reaction at the atomic scale thanks to recently developed thin silica films grown on metals as a well-defined silica support. Indeed, beautiful high-resolution scanning tunnelling microscopy (STM) images of the bilayer film are reported in the paper. Therein, the authors discussed also surface sensitive data obtained by XPS, noting that a simple discussion based on binding energy (BE) chemical shift could be misleading without associating complementary characterization techniques. In the second example, the authors studied the dynamics of the Au NPs on MgO, under low pressure CO₂, by means of STM. In this way, they were able to observe the reaction, which is confined to the rim of the particles where the molecules of CO₂ adsorb and convert into

oxalate species as confirmed by infrared reflection-absorption spectroscopy (IRAS).

The session was concluded with the contribution by **Dr Stig Helveg** (Haldor Topsoe, Denmark) on the detailed study of step edge structures on TiO₂ (001) by means of atomic resolution TEM and STM. [DOI: 10.1039/c7fd00222j] After a careful analysis, taking into account electron dosage and impact of this on the structure of the material, the authors were able to identify double step edges and several small differences in the periodicity of the “ad-molecule structures” (ADM) along and across the double step edges. This ADM structure is a surface reconstruction which covers the surface with rows of TiO₃ replacing bridging O to relieve large tensile of unreconstructed surfaces. The structural agreement between single crystals and NPs holds promise that this combined STM and TEM approach can be used to study complex catalytic systems. In the general discussion, it was emphasised that these *in situ* electron microscopy experiments remain challenging and therefore should be considered as the current state-of-the-art.

Session 3: Control of catalytic nanoparticle synthesis

The day continued with the third session of the meeting, regarding the synthesis of nanoparticles for catalytic reactions, chaired by Prof Bob Tooze.

The first part of the session was opened by **Prof Laura Prati** (Università degli Studi di Milano, Italy) who introduced her work entitled “*Gold as a modifier of metal nanoparticles: effect on structure and catalysis*” where she presented the preparation of bimetallic Au-based particles (Pt, Pd, Ru and Cu) on a carbon support by the sol-immobilisation method, which is known to provide a good control of size. [DOI: 10.1039/c7fd00223h] Despite similar metal dispersions, the selection of the second metal was of key importance for the resulting activity. Au-Pd and Au-Cu bimetallic systems show a clear synergistic effect in the oxidation of benzyl alcohol; In contrast, the addition of Pt to Au seemed to have a detrimental effect on the catalytic performance, whereas Au and Ru do not seem to form alloys but instead core-shell structures. The second paper entitled “*One pot microwave synthesis of highly stable AuPd@Pd supported core-shell nanoparticles*” was presented by **Dr Jennifer K. Edwards** (Cardiff University, UK). In this work, microwave decomposition of metal precursors was presented as a one-step quick synthetic method to form well-defined metal nanoparticles without the need of additional reducing agents and minimum post-synthesis washing steps (DOI: 10.1039/c8fd00004b). In the case of bimetallic particles, this method led to the formation of Au core surrounded by an Au-Pd shell, in contrast to the bimetallic alloy formation achieved by the sol-immobilisation methods. Even more interesting is the high stability of these core-shell bimetallic nanoparticles, which show constant activity in several consecutive runs for the synthesis of hydrogen peroxide. The session continued with the presentation of **Dr Laura Torrente Murciano** (University of Cambridge, UK) entitled “*Continuous synthesis of hollow silver-*

palladium nanoparticles for catalytic applications”, where a novel flow system for the continuous synthesis of nanoparticles with tuneable sizes was presented [DOI: 10.1039/c8fd00001h]. This innovative approach consists of a number of coiled flow inverter (CFI) microreactors connected in series which enable, for the first time, the separation of the nucleation, growth of cores and galvanic displacement stages leading to the formation of reproducible hollow bimetallic alloys nanoparticles. Bimetallic Ag-Pd hollow particles show a higher activity than their monometallic and solid Ag-Pd alloy counterparts in the reduction of 4-nitrophenol used as a model reaction. These results open the door to the design, understanding and



exploitation of hollow nanoparticles in catalysis.

A lively general discussion followed these presentations, prompted by the diversity of the methods, focusing on the ability to tailor the reactivity of nanoparticles by exploring synergistic effects induced by the metal-metal interaction in binary alloys. The role of the reducing agents in the synthesis of the bi-metallic systems was highlighted, and especially their effect on determining the metal’s distribution within the NPs (e.g. formation of alloys, core-shell and hollow structures). In this regard, flow reactors offer the opportunity of quickly varying not only the physical parameters (e.g. temperature) but also the chemical environments within milliseconds. The control achieved in the design of metal nanoparticles by these different methods, at the core of this event, was stressed, in addition to the importance of using theory to predict not only the resulting structures but also their respective reactivity. As expected when considering synthetic methods for nanoparticles, comments about their scalability were raised. In this context, flow protocols can be designed for the translation of the different synthetic procedures where scalability can be easily achieved by increasing the number of reactors in series.

The discussion extended through the coffee break, after which the session continued with two additional presentations. The first talk was by **Dr Scott Rogers** (University College London, UK) on a paper entitled “*Supported metal nanoparticles with tailored catalytic properties through sol immobilisation: applications for the hydrogenation of nitrophenols*”, where the importance of carefully adjusting the conditions of colloidal synthesis, i.e. temperature and solvent, was further emphasised for the manipulation of the catalyst structure and reactivity. The principle was illustrated for the synthesis of Pd nanoparticles supported on TiO₂, with smaller particles achieved at lower

temperatures, presenting higher activity towards the hydrogenation of p-nitrophenol and increased stability on consecutive runs; slightly bigger NPs are formed at high temperatures, where aggregation seems to take place (DOI: 10.1039/c7fd00216e). The following work was introduced by **Prof Philip Davies** (Cardiff University, UK) who emphasised the role of the support and its functionality in the design of nanoparticle-based catalysts in their paper entitled "*The deposition of metal nanoparticles on carbon surfaces: the role of specific functional groups*". In their work, they use highly ordered pyrolytic graphite crystals (HOPG) as model surfaces to understand the effects of specific functional groups including hydroxyl, ether and carbonyl groups on the formation of Au nanoparticles. In this elegant approach, by a combination of AFM and XPS characterisation, they demonstrate the direct involvement of hydroxyl groups in the reduction of gold ions, whereas carbonyl and ether groups promote the nucleation of Au³⁺ ions (DOI: 10.1039/c7fd00210f). These results reveal the actual effects of previously reported carbon acid treatments, providing initial rationale behind the effect of oxygen species on the support to stabilise gold nanoparticles.

The enormous complexity of supported nanoparticle-based catalysts was the focus of the following discussion. In general, the importance of *in situ* characterisation during the synthesis of nanoparticles was acknowledged to reveal the effect of key

Figure 3: Attendees are presented with the outlines of the Loving Cup ceremony of the Faraday Discussions, where toasts are given to the memory of Mr Marlow, Angela and Tony Fish, and to the Faraday Division.

synthetic parameters such as temperature, solvent, metal precursors, support functionality, reducing agents, etc., and to understand and consequently control the resulting catalytic systems.

This stimulating day concluded with the conference dinner at the Royal Society in a more informal manner including the famous celebration of the Loving Cup tradition (Figure 3).

Session 4: Application of new nanoparticles structures as catalysts

The final day of the event was focused on the applications of new nanoparticles-based catalysts, chaired by Prof Chris Hardacre. The session was opened by **Prof Chris-Kriton Skylaris** (University of Southampton, UK), with a talk entitled "*DFT calculation of oxygen adsorption on platinum nanoparticles: coverage and size effects*", which investigates nanoparticle structure and chemistry of the state-of-the-art catalysts for hydrogen fuel cell electrodes. [DOI: 10.1039/c7fd00218a] Addressing indirectly the question of optimal nanoparticle sizes, the authors acknowledged the scope of the problem is beyond standard computation and focus on the effects of O coverage on chemical properties. In their work, it was observed that, as nanoparticle sizes grow, the adsorption energies decrease and converge to bulk surface values, correlating also with d-band properties. The subsequent discussion focused heavily on the capabilities of the methodology developed and used by Prof Skylaris, namely the linearly scaling ONETEP package and the

recent implementation of a linear-scaling implementation for metals, [DOI: 10.1063/1.5001340] provoking memories of Wilke Dononelli's presentation of CCSD(T) on Day 1. Such approaches are beneficial for large systems, beyond the maximum of 309 atoms addressed by Skylaris and co-workers in this presentation, and can help to improve the understanding of chemistry on large nanoparticles. From a chemical perspective, several calls were made to look at benchmarking of these results with experiments, and consideration of whether a surface oxide has successfully formed; both ideas were acknowledged as being of value in future work.

In the second presentation, **Dr Katharina Brinkert** (California Institute of Technology, USA) discussed the development of technologically advanced III–V semiconductor absorbers coupled via an interfacial film to an electrocatalyst layer for photo-electrochemical (PEC) cells for H₂ production from water. [DOI: 10.1039/c8fd00003d] The authors demonstrate that shadow nanosphere lithography (SNL) is an auspicious tool to systematically create three-dimensional electro-catalyst nanostructures on the semiconductor photoelectrode, through controlling the NP morphology and optical properties. First results are demonstrated by means of the photo-electrochemical production of hydrogen on p-type InP photocathodes where hitherto applied photo-electrodeposition and SNL-deposited Rh electro-catalysts are compared based on their J–V and spectroscopic behaviour. The authors show that smaller polystyrene particle masks achieve higher defect nanostructures of rhodium on the photoelectrode, which leads to a higher catalytic activity and larger short circuit currents. The following discussion considered then the future steps for this exciting work.

After the morning tea break, the session continued with the presentation by **Prof Paul Sermon** (Brunel University, UK) entitled "*Nanoengineering ABO₃ active sites from low-energy routes (TX100-stabilised water-in-oil micro-emulsions, surface segregation and surface complexation on colloidal AlOOH/sol-gel Al₂O₃ surfaces) for pollution control catalysis*" where water-in-oil micro-emulsions were used for the formation of BaCeO₃ and LaCoO₃ particles, with applications in CO and propane oxidation and phenol removal from aqueous streams respectively (DOI: 10.1039/c8fd00006a). Such alternative synthetic routes as the use of micro-emulsions opens the door to novel, reproducible and controllable ways of producing perovskite-type nanoparticles for a wide range of applications. The last talk of this session was given by **Prof Andrea E. Russell** (University of Southampton) discussing the paper entitled "*Effects of heat treatment atmosphere on the structure and activity of Pt₃Sn nanoparticle electro-catalysts: a characterisation case study*". [DOI: 10.1039/c7fd00221a] The authors address the effect of thermal post synthesis treatment on the quantitative and qualitative composition of Pt₃Sn NPs by applying a multiple bulk and surface sensitive characterization techniques approach. A correlation of the structural features of these samples with the electro-catalytic performance for CO, methanol, ethanol and 1-butanol oxidation was also drawn. This talk stimulated further discussion as to what would be the most appropriate methodology for obtaining an accurate chemical

speciation and quantitative composition of the NPs. Obviously, there is not a general answer to this question, however the comforting outcome of this study is that for the NPs investigated, the different methodologies indicate the same qualitative trend in composition amongst them.

Concluding remarks

The event was concluded with an inspiring and stimulating lecture by **Prof Cynthia Friend** (Harvard University, USA) where she elegantly summarised the community's aspiration to predict catalysts' reactivity and selectivity based on fundamental understanding. In order to achieve this ultimate goal, atomistic models are of paramount importance to enable the design of real systems. Within this context, theoretical developments, including reaction kinetic models, are presented as a driving force for the understanding of reactions on the surface of nanoparticles. There are different flavours of DFT approaches, where models vary in terms of detail and thus accuracy, creating the need for experimental validation of theoretical methods for electronic structure calculations require experimental validation. Close collaboration between experimentalists and theorists is thus of key importance. Particularly, accurate measurements of adsorption energies (calorimetry, TPD), bond distances (diffraction, EXAFS, imaging) vibrational frequencies (IR, Raman) chemical shifts (CPS) and electronic structures are required information to benchmark theoretical models and to validate reaction mechanism. These efforts should be combined with the modelling of nanoparticles and their interaction with the supports, not only considering model surfaces but also taking into consideration structural complexities (the presence of defects, vacancies and charge transfer). During the event, it was evident that there is a plethora of methods for the synthesis of metallic nanoparticles, especially focused on binary system, ranging from well-established synthetic strategies such as wet impregnation and sol-immobilisation routes, to novel approaches such as microwave synthesis, microemulsion and flow systems. It was noted that special attention should be paid to the activation pre-treatments and their implications to gain the needed knowledge related the evolution of the systems. Two approaches can be adapted towards this aim: single crystal model systems, including thin-film integrated with spectroscopy methods, as well as real models. Indeed, *in situ* and *operando* methods provide knowledge of how catalysts evolve under catalytic conditions. A combination of imaging and spectroscopy, provides unique and highly valuable insights into catalyst changes, materials structure and composition and their dependency on ambient gas pressure and process temperatures. Metastable states can present surprisingly high reactivities, but present the challenge of their stabilisation. The importance of reaction kinetics, including the elucidation of elemental steps and the material structural rearrangement, was

identified as an additional important focus area for the design of future catalytic systems.

The complexity of some of the above mentioned challenges could be facilitated by better benchmarking and standardisation protocols for both theoretical and experimental studies, which identify the key characteristics of improved and enhanced catalysts. In this context, exciting contributions can be expected from the application of statistical approaches and machine learning contributions for future catalyst discovery and synthesis.¹¹ This final stimulating lecture provided a fertile ground for thoughts to the community that departed after the closure of the meeting until the next Faraday Discussion event in the field: "Reaction mechanisms in catalysis" to be held in Burlington House, London during 22nd – 24th April 2020.

Figure 4: Picture of the community during the concluding remark lecture by Prof Cynthia Friend.

Conclusions

This Faraday discussion meeting, focused on the design of nanoparticle systems for catalysis, was a unique opportunity to bring together the community in a highly scientific stimulating manner. Its individual format, focused on deep and critical discussion, helps not only to evaluate the state-of-the-art of the field but also, and most importantly, set the guidelines for future developments. Without a doubt, a combination of new and controllable synthetic routes guided by in-situ characterisation techniques and theoretical predictions is required to tackle the complexity of the supported nanoparticle catalytic systems.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

‡ Footnotes relating to the main text should appear here. These might include comments relevant to but not central to the matter under discussion, limited experimental and spectral data, and crystallographic data.

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etc.



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