

Royal Society of Chemistry

Dalton 2025

University of Warwick, 1-3 Apr 2025

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An Automated, Modular, Chemistry Robotics Platform for Rapid Data Generation and Statistical Model Development for Palladium Catalysed Cross-Coupling Reactions

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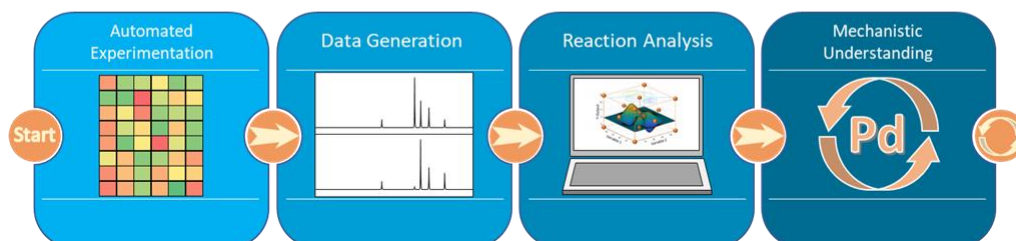
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Reaction automation benefits chemists by offering optimisation acceleration, increased productivity, higher quality more robust data, and improved reaction safety, amongst others. These platforms can be used to assist chemists in looking at complex catalytic reaction processes where details of the nature of catalysis itself can be unravelled. Numerous catalytic cycles often compete with other pathways e.g., side products and catalyst decomposition, adding overwhelming levels of complexity to sift through. With many reaction variables playing a role in pre-catalyst speciation and reaction progression, often slight changes can have profound effects on overall reaction turnover.¹



Figure 1 Top: Image of the Chemspeed automation platform and Crystal Powderdose used for catalytic reaction screening and optimisation of reactions for mechanistic insights. Bottom: Workflow procedure from automated experimentation, large data generation, and reaction analysis for greater understanding of palladium catalysed reactions.

Understanding this reaction complexity can be eased by using automation, high-throughput experimentation, and other optimisation techniques.² Employing robotic platforms (



- Top)

allows complete reaction automation *i.e.*, solid, and liquid handling, temperature and stir control, the use of air sensitive reagents and at-line LCMS analysis.³ A variety of reactions – organic synthesis and palladium catalyzed cross-coupling reactions - have been explored using various experimental methods typically used in the lab but in an automated fashion. This automated methodology has allowed us to gather large quantities of data and delve deeper into reaction paradigms for mechanistic insights and optimising synthesis (Figure 1 - Bottom).

1. Fairlamb *et al.*, *Nat. Commun.*, 2024, **15**, 3968
2. Sach *et al.*, *Science*, 2018, **359**(6374), 429
3. Cooper *et al.*, *Nature*, 2024, **635**, 890

Understanding Side Reactions in Suzuki-Miyaura Cross-Couplings Reactions Using HTE

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Suzuki-Miyaura Cross-Coupling (SMCC) reactions are one of the most powerful reactions within the synthetic chemists toolkit – critical to the agrochemical, material, and pharmaceutical industries.¹ Commonly, when cross-coupling new heteroaryl substrates, competing side reactions can occur. The factors affecting side reactions, such as protodeborylation, are understood in the main.² However, a side reaction that is less understood is protodehalogenation, which relates to the electrophilic organohalide coupling partner.

A class of molecule that is prone to protodehalogenation is that of unsaturated lactones such as 2-pyrones³ and coumarins.⁴ Despite examples of this side-reaction occurring for these substrates and other heterocycles, there is little understanding into what factors affect this process.

As the SMCC reaction typically consists of many variables that can influence cross-coupling efficacy, gaining mechanistic understanding can be challenging due to the number of reactions that must be conducted, *i.e.* the complete reaction space. Therefore, high-throughput experimental (HTE) and Design of Experiment approaches are well suited to screening different pre-catalysts, ligands, bases, solvents, temperatures, reaction times, and nucleophilic coupling partners to gain in-depth mechanistic understanding into this side reaction. The results of this study, coupled with appropriate data science tools, will be reported in this presentation.

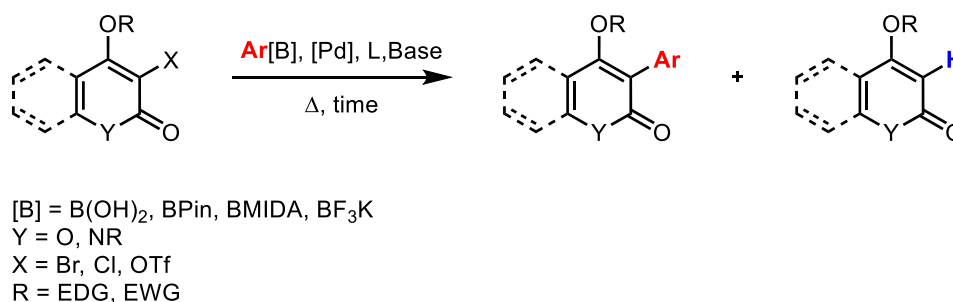


Figure 2: Factors that could have an affect protodehalogenation in unsaturated lactones and lactams

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Extracting mechanistic information from an open dataset for a pharma -relevant Suzuki-Miyaura cross-coupling reaction

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Open reaction datasets, particularly those gathered through high throughput experimental (HTE) reaction screening campaigns, hold considerable value in downstream data analysis and reaction understanding. Data can be used to reveal important trends. While there is a great deal of reaction complexity associated with Suzuki-Miyaura cross-coupling (SMCC) reactions, as informed by many independent mechanistic studies over the years, one can bring out essential trends through detailed data analysis. In this study, we have taken an open reaction dataset reported by Pfizer and evaluated the properties of closely-related substrates, the effect of reaction solvent, base and ligands¹. Through a detailed analysis of the reaction outcomes we have focused on the occurrence of a common side-product in SMCCs, resulting from protodeborylation of the organoboron coupling component. In our analysis we have delineated a number of interesting trends, which reveals value in evaluating side-product(s)/main product yields. A Shiny app has been developed for the rapid evaluation of the Pfizer SMCC reaction dataset, as well as new SMCC reaction data.



Figure 3 - Screenshot of shiny app window, showing an example heatmap. The tab on the left displays the different parameters: four choices of graph, group choice and the different measures associated with the graph selected. The left of the app contains the plotting window in which the graph selected will be displayed.

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1. Synthetic Fuels

- Synthetic fuels will play a key role in the energy transition as so called "drop-in fuels".
- They will also be used for applications for which current battery technology is unsuitable, i.e., aviation, marine and heavy goods transportation.



Figure 1. Proposed process flow diagram for the production of synthetic fuels via Methanol/DME.

2. Zeolites

- Highly ordered, porous aluminosilicates widely used as catalysts, membranes and for molecular sieving.
- Substituting Si for Al results in the formation of acidic, active sites:

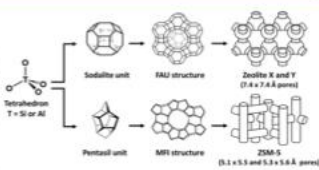
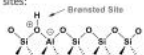
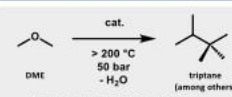


Figure 2. Hierarchical structures of ZSM-5 and zeolite Y.

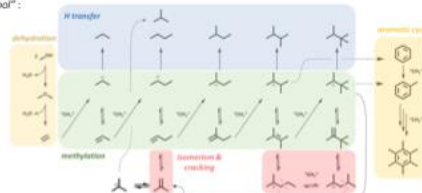
3. Methanol-to-Gasoline Chemistry

- MTG chemistry was first reported in 1880, catalysed by "hot" ZnO.
- Current commercial processes use zeolite catalysts (ZSM-5, zeolite-β and zeolite Y).



Scheme 1. Target reaction of DME to triptane.

- Catalysis proceeds via dehydration of oxygenates to ethylene which then reacts further in the "carbon pool":



Scheme 2. Carbon pool mechanism for the formation of isoparaffins and aromatic components.

The Chemical Challenge

- Suppressing the formation of polymethylbenzene derivatives, favouring instead branched paraffins.
- Prevent deposition of carbonaceous material in the zeolite pores.
- Overcome the hydrogen deficiency that exists for the conversion of DME to isoparaffins.

2. Packed Bed Flow Reactor Design

- Industrially, the MTG process generally operates at ca. 350 °C and 20 bar over H-ZSM-5. However, this temperature is generally too high when selecting for triptane which is rapidly cracked at this temperature.

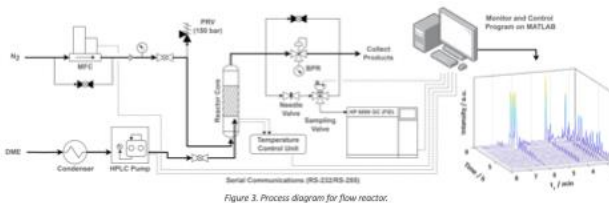


Figure 3. Process diagram for flow reactor.

The Engineering Challenge

- Design and construct a flow reactor to perform reactions at elevated temperatures and pressures.
- Pressurise DME to process conditions (normally limited by its vapor pressure 3-4 bar).
- Online sampling with a gas chromatograph.
- Designing a MATLAB program to communicate with, monitor and read data from different electrical components using different serial communication protocols.

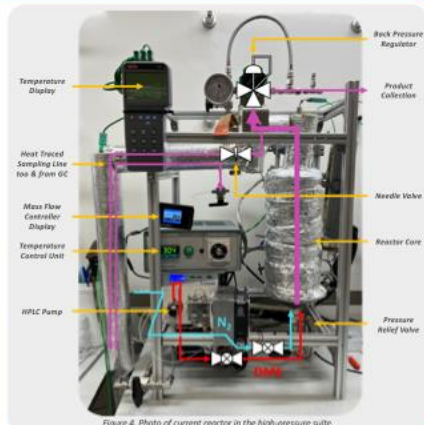


Figure 4. Photo of current reactor in the high-pressure suite.

6. Results

Analysing Product Streams

- Reactions result in complex mixtures of hydrocarbons which are analysed online and at the end of a reaction.
- Components are identified using external standards and GC-MS.

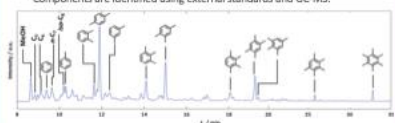
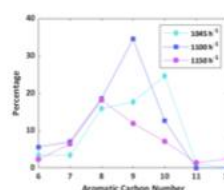


Figure 5. Sample GC-MS data from a reaction of DME over ZSM-5.



$$\text{Gas Hourly Space Velocity} = \frac{\text{Volume of gas passed over catalyst}}{\text{Volume of Catalyst bed} \times h}$$

$$\text{Weight Hourly Space Velocity} = \frac{\text{Mass of Reactant}}{\text{Mass of catalyst} \times h}$$

7. Conclusions

7. Future Work

9. Acknowledgments

10. References

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Mechanism-led Development of Lewis-acid Catalysts for Amide-bond Formation

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Amide bond formation is a main staple reaction within all chemical disciplines with a study in 2014 showing that 50% of production reactions encompass them¹. Although this could imply that amide formation had been well researched, more recent studies have uncovered key mechanistic features which may provide a route to improving and discovering new optimized catalysts².

This work is focused on developing a deeper understanding of how commercially available Lewis acid catalysts are able to perform in a solventless amidation reaction in a model carboxylic acid and amine system comparable to conditions used on site industrially. By combining NMR, kinetic and robotic studies new insight into the factors controlling the outcome of these reactions has been gained. In particular, analysis using the Burés kinetic method³ has allowed for an understanding of the speciation of the Lewis acid catalysts. In addition, NMR studies have provided key information about the initial steps in the activation of the pre-catalyst.

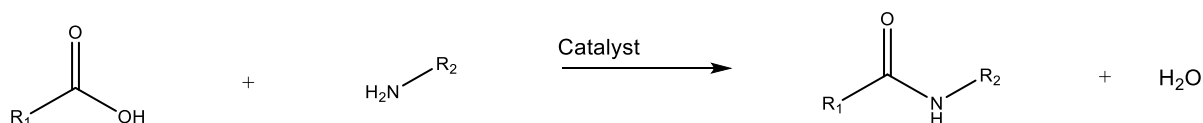


Figure: Simple amide bond formation reaction

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Using Machine learning to Access Challenging Hydrogenations: A combined theoretical and experimental approach

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Asymmetric hydrogenation reactions of tetra-substituted olefins provide direct access to compounds containing 1,2-contiguous stereocentres, which are of great relevance to the production of pharmaceuticals. However, compared to di- and tri- substituted substrates, the enantiomeric excess (ee) of these reactions is generally poor, and thus, fewer examples have been reported in the literature.¹

In this work, machine learning techniques were initially trained to predict the ee of asymmetric hydrogenation reactions of tetra-substituted olefins using examples that have been reported in literature. Several regression and classification machine learning methods were implemented, with the best models producing a mean absolute error of 9.95% ee and an accuracy of 89%, respectively.

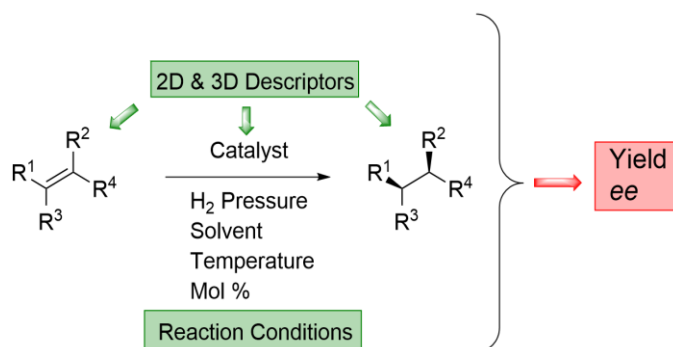


Figure 1. Asymmetric hydrogenation reaction of tetrasubstituted olefins.

The fitted machine learning models now hold a useful tool for reaction optimisation of asymmetric hydrogenation reactions of tetra-substituted olefins, while giving valuable insight into the transition-metal chiral catalysts that result in successful reactions.

However, due to the reporting bias that exists in literature publications,² more experimental data of reactions leading to lower ee values is required to improve the predicted performance of machine learning models. Thus, further work has focussed on creating a more diverse experimental dataset to counteract this imbalance and probe the current landscape of transition-metal/ligand/substrate combinations of this reaction.

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Isolable, Catalytically-Relevant Pre-transmetalation Intermediates in Csp²-Csp³ Suzuki-Miyaura Cross-Couplings

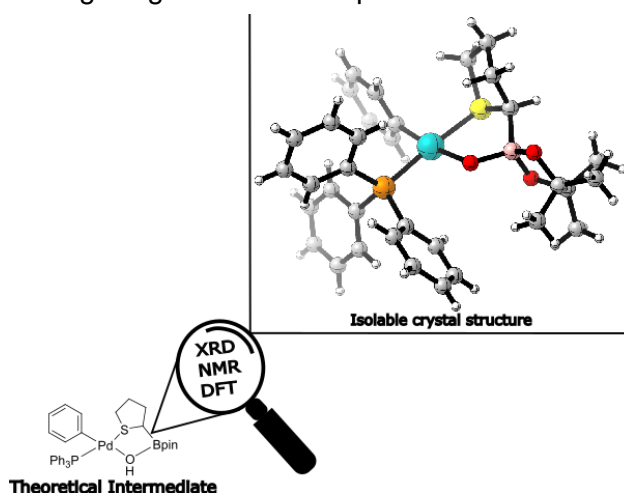
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The Suzuki-Miyaura cross-coupling (SMCC) reaction¹ is among the most important reactions in synthesis, providing pathways that make value-added products commercially feasible.²⁻⁵ While the SMCC is most commonly employed to make new Csp²-Csp² bonds, there is growing interest in expanding this to make other kinds; notably Csp²-Csp³.⁶ However, due to the "black-box" nature of certain organometallic steps, such as the transmetalation, it is difficult to ascertain how to best optimize these reactions. To this end, we have recently discovered an on-cycle isolable Csp²-Csp³ pre-transmetalation intermediate, complementing synthetic methodology work) providing insight into the complex nature of these reactions (see figure).



sc-XRD Structure of an on-cycle pre-transmetalation intermediate, with both experimental and theoretical evidence provided for its existence.

Complementary findings by density-functional theory (DFT) and experimental studies (NMR, XRD, ATR/FTIR) provide a detailed picture of the of transmetalation step in this system.

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Utilizing AI to Predict Iron-Catalyzed Kumada Couplings

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In 1971, Kochi demonstrated that iron(II,III) chlorides could catalyze the generation of C-C bonds through vinylation of Grignards with alkenyl halides.¹ Further C-C bond generation schemes using Grignards and organic halides were demonstrated in 1972 by Kumada using nickel catalysts.² This was the first cross-coupling catalyzed by Ni or Pd, and the reaction was subsequently named the Kumada coupling.

Since 1972, extensive research has been conducted on Kumada couplings, and a variety of transition-metal catalyzed schemes have been demonstrated. However, they are mainly catalyzed by palladium and nickel.³ Palladium catalysts are unsustainable and expensive, and nickel catalysts are often toxic – both have negative environmental impacts.^{4,5,6} As a result, there is a growing trend for non-toxic, earth-abundant metal catalysts – such as iron catalysts.⁷

Our project aims to accelerate the development of iron-catalyzed Kumada couplings by using machine learning to discover new iron-mediated Kumada couplings and predict ideal ligands, solvents, and temperatures. We have curated a dataset of over 500 iron-catalyzed Kumada couplings and will use quantum mechanical featurization to convert our data into a machine-readable format. We will test several different algorithms and expect our selected algorithm to not only assist in yield optimization and catalyst design but also provide mechanistic insight by analyzing correlations between selected descriptors and model accuracy.

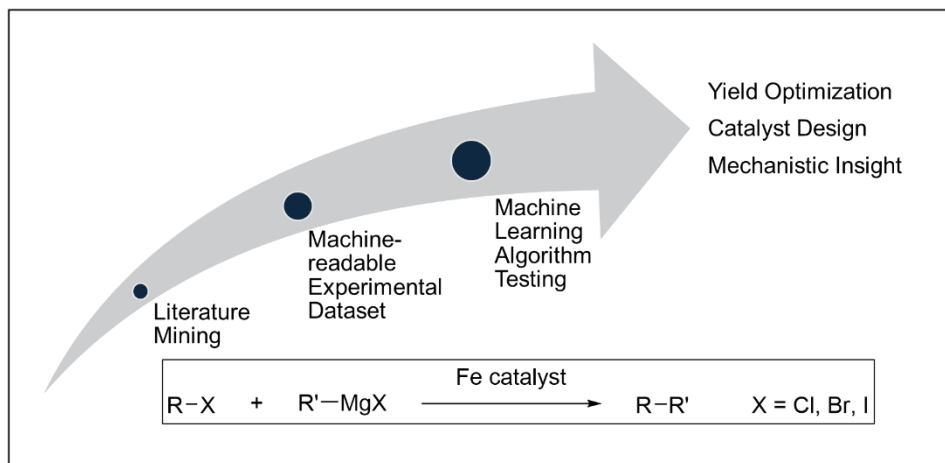


Figure 1. Overall Project Flowchart and Iron-Catalyzed Kumada Coupling Reaction Scheme

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Mechanistic understanding of iron-catalysed nucleophilic substitution of alcohols

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Alcohols are ubiquitous throughout chemistry, with their cheap and abundant nature providing pathways for the synthesis of more complex and functionalised molecules. Similarly, iron is becoming an increasingly sought after option for catalysis over the precious, platinum group metals.

More emphasis is being put on developing iron catalysed reactions in order to drive towards sustainability, however there is still limited mechanistic understanding of these reactions due to obstacles when working with paramagnetic iron species. Here we investigate an FeCl₃ and AgSbF₆ catalytic system, that has been used for a range of inter- and intramolecular processes, including the substitution of unactivated alcohols by sulfonamides¹ and the Friedel-Crafts-type arylation of unactivated secondary alcohols to form alkylated products². The aim of this study is to explore the mechanistic role iron plays in the catalysis of alcohol substitution, enabling a deeper comprehension of this area. Increased mechanistic understanding allows for a maximisation of catalytic efficiency, invaluable to many industries looking to reduce costs and clean up syntheses, as well as the potential for the development or creation of more complex processes. Here, kinetics and speciation studies allow the investigation of the reaction mechanism, allowing different species within the reaction to be tracked, and the effect of slight changes in the catalytic system to be monitored, showcasing the role inter-species interactions and the importance of developing an effective and efficient catalytic system.

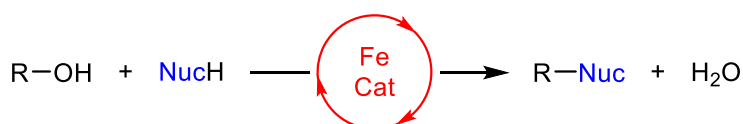


Figure 1: The reaction scheme for the iron catalysed nucleophilic substitution of alcohols

References

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Hydrophosphination of aryl isocyanates towards cyclic phosphines

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Phosphinines are ubiquitous within the field of homogeneous catalysis as ligands for some of the mostly widely used coupling reactions such as the Suzuki-Miyaura and Buchwald-Hartwig reactions.¹ The Kays group have previously shown that secondary aryl phosphines undergo catalytic hydrophosphination with isocyanates using an iron(II) terphenyl complex $[\text{Fe}^{\text{MesTer}}_2]$, with the possibility to insert two isocyanates into a single P–H bond forming a *P,N,N*-biuret.² However, their reactivity towards primary phosphine was not investigated. More recently, Liptrot and co-workers developed a ‘one-pot’ system to access amide functionalised phosphines from phosphorus(III) esters by reducing the esters to the primary and secondary phosphines and PH_3 itself, followed by addition of a single isocyanate to each P–H bond.³

Herein we present the catalytic hydrophosphination of isocyanates towards FcPH_2 to obtain *N,P,N*-biurets (Figure 1, A) and its surprising reactivity in the presence of higher equivalents of phenyl isocyanate. When using excess isocyanate at elevated temperature and catalyst loading to try and facilitate the addition of multiple isocyanates into a single P–H bond, formation of cyclic phosphines was observed (**B** and **C**, Figure 1) which have been characterised spectroscopically and crystallographically. This represents the first catalytic method to obtain amide based cyclic phosphines. Preliminary mechanistic studies have been conducted to determine the mechanism for the formation of the cyclic phosphines.

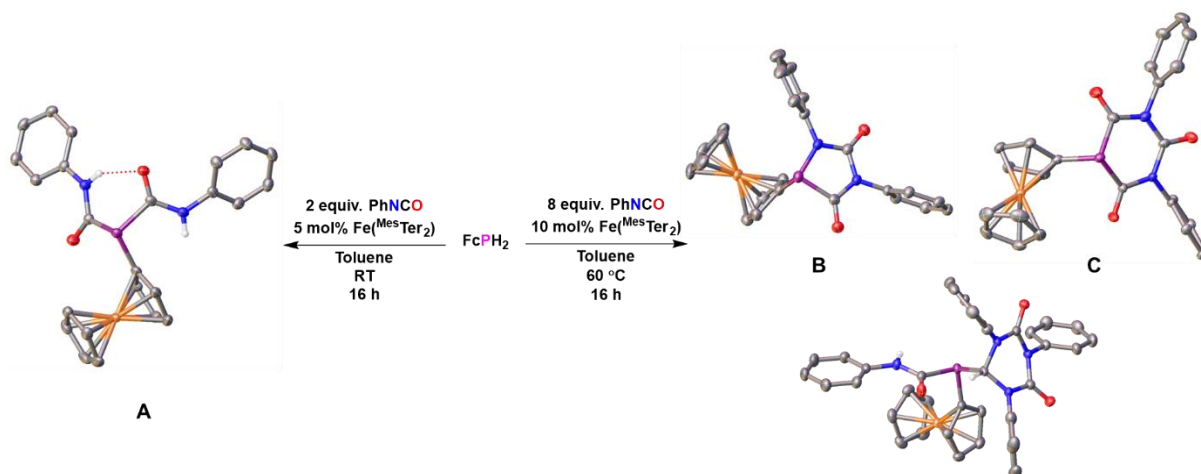


Figure 1. Divergent reactivity of FcPH_2 with excess PhNCO to access cyclic phosphines (**B** and **C**).

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A Molecular Probe for the Study of Mn-Catalysed C-H Bond Functionalisations using Time-Resolved Mass Spectrometry

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Organometallic reagents stand at the forefront of catalysis, pivotal in driving advancements in pharmaceuticals, agrochemicals, and advanced materials synthesis. The quest for sustainability in this domain is fuelled by the scarcity and potential toxicity of precious metals in catalytic reactions. To address this issue manganese is emerging as a promising earth-abundant elemental alternative to precious metals.¹

Recent work utilising time-resolved mass spectrometry (TRMS) allows mechanistic insight to be gained in catalytic chemistries, especially when paired with additional mass spectrometry techniques such as collision-induced dissociation (CID), ion mobility, and ion spectroscopy.

We present a TRMS investigation^{2,3} into a Mn-mediated alkyne insertion reaction, employing a novel phosphonium-tagged 5-membered manganacycle. There is evidence for initial CO loss, formation of a 7-membered manganacycle intermediate. A competing photoinduced demanganation process is further revealed.⁴

The reaction was initiated by irradiation with a UV diode (365 nm or 405 nm), the power and wavelength of which was found to have a large effect on the rate of the photodecomposition reaction, and therefore on the conversion of the expected alkyne insertion reaction (Figure 1).

The use of pressurised sample infusion (PSI), where an overpressure of N₂ was applied to the reaction vessel to a flow of the reaction mixture into the mass spectrometer, enabled the study of the air-sensitive system.⁵ The experimental set-up allowed real-time reaction monitoring observing the evolution of species and intermediates present in the mixture over time.

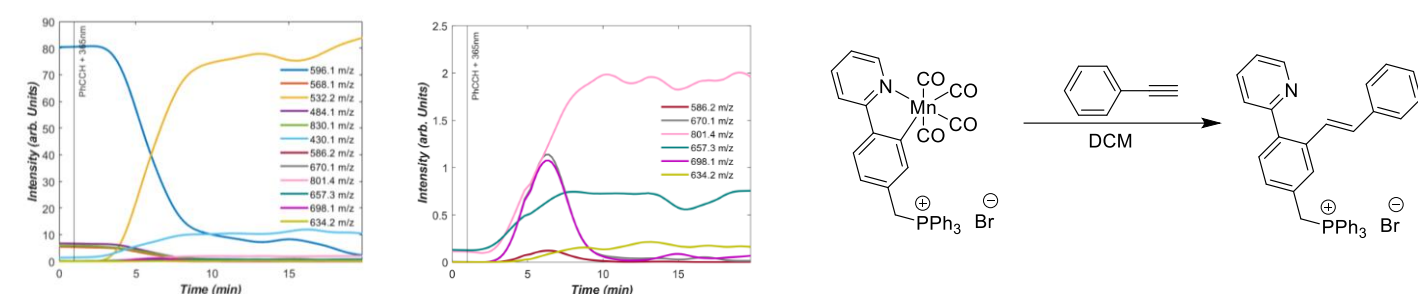


Figure 4. TRMS of reaction of a phosphonium-tagged 5-membered manganacycle with phenylacetylene (left); (middle) the time profiles of low intensity species; (right) reaction being studied.

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Kinetic investigation of ruthenium mediated *anti*-Markovnikov hydration of terminal alkynes by *in-situ* NMR monitoring

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The hydration of terminal alkynes is an atom-economical and chemically green method of obtaining desirable carbonyl compounds from feedstock chemicals. While many different systems are known for the Markovnikov addition, the *anti*-Markovnikov addition to the more chemically "rich" aldehyde remains limited.

In 2014, Herzon, Li, and Zeng reported a bipyridine catalyst, **1**, for the highly *anti*-Markovnikov selective hydration of terminal alkynes.¹ Although extensive reaction optimisation was performed, there has yet to be any investigation of reaction kinetics or mechanism, instead being inferred from older phosphorous based systems.² In 2023, Muldoon *et al.* reported a series of bipyridine-analogous, 2-(2-pyridyl)benzoxazole (PBO) ligands, for Wacker oxidation chemistry.³ The electronic asymmetry of these were found to be of great importance to the overall activity of the complexes, and may be of interest for the hydration of terminal alkynes.

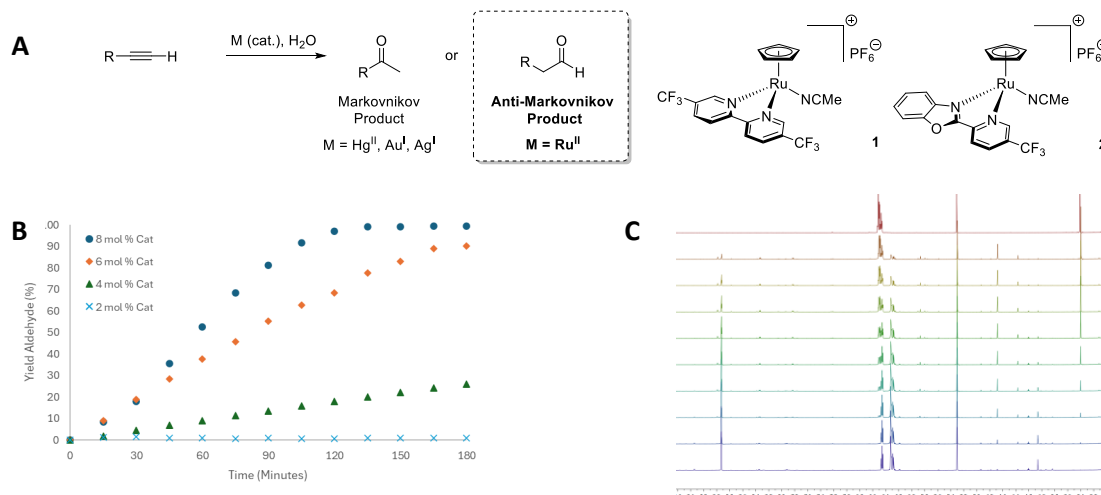


Figure – A) General scheme for hydration of terminal alkynes and structures of ruthenium catalysts **1** & **2**. **B)** Yield vs time plots at different mol% **1**. **C)** *In-situ* NMR waterfall plot for reaction monitoring.

Our work aims to provide both a kinetic investigation of the previously reported catalyst **1**, as well as kinetic comparison between bipyridine catalyst **1** and PBO catalyst **2**, investigating the use of this new family of ligands in this class of reaction. NMR spectroscopy has been utilised for *in-situ* monitoring of NMR-scale reactions. Variable Time Normalisation Analysis (VTNA) for both systems has been performed to probe and compare the reaction mechanism.

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Rhodium-catalysed hydrogenation of nitrous oxide

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Nitrous oxide (N₂O) is a long-lived gas that accumulates in the atmosphere, contributing to climate change as a potent greenhouse gas and leading to ozone depletion in the stratosphere.¹ Although chemical activation is challenging, exponentially-increasing anthropogenic emissions of N₂O make it imperative that energy efficient methods are developed to remediate point sources of this atmospheric pollutant.² In this context, the hydrogenation of N₂O to afford N₂ and H₂O is an attractive, thermodynamically favourable, yet surprisingly undeveloped transformation, using either heterogeneous or homogeneous catalysts. Of the limited examples of heterogeneous N₂O hydrogenation described in the literature, the use of platinum group metal catalysts stands out for the mild operating temperatures involved (50 – 150 °C).³ Molecular complexes of the platinum group metals have additionally been investigated as homogeneous catalysts, with seminal work on the application of ruthenium pincer complexes reported by Milstein in 2017 (TON = 417, 48 h).⁴

Inspired by these developments in homogeneous catalysis and building upon our work with rhodium pincer complexes, we became interested in assessing the catalytic activity of rhodium(I) pincer complex **1**. Herein we report on the discovery of hidden heterogeneous catalysis in the hydrogenation of nitrous oxide when using **1**. Commercially available and bench-stable [Rh(COD)(OH)]₂ was thereafter identified as a more effective catalyst precursor, enabling the hydrogenation of nitrous oxide at RT with over 3000 catalytic turnovers per rhodium.

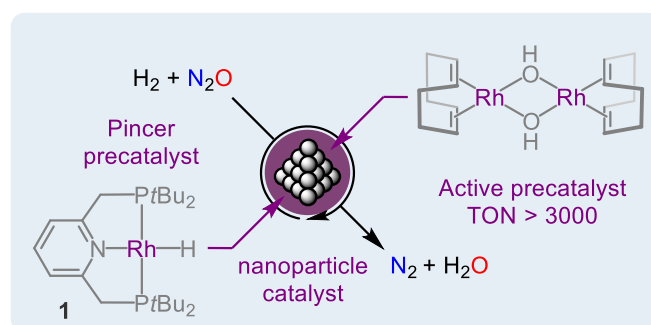


Figure 5. Rhodium nanoparticle catalysed hydrogenation of nitrous oxide.

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Iridium Mediated Electro-Hydrogenation with H₂O at Minimal Overpotential and the Role of Specific Acid Co-Catalysis

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Hydrogenation is essential for chemical synthesis, bio-feedstock upgrading, and energy storage via liquid organic hydrogen carriers. Electrocatalytic hydrogenation (ECH) offers a sustainable alternative to thermochemical reactions with gaseous H₂, or transfer hydrogenation that creates stoichiometric waste from hydrogen donors. Persistent key challenges of ECH are to achieve high Faraday efficiencies (FE) by suppressing H₂ evolution as the dominant parasitic process; to minimize overpotentials for high energy efficiency; and to enable H₂O as the most sustainable proton source for ECH. The presented work will show that [(Cp*)Ir(bpy)(H₂O)]²⁺ (**1**) can serve as an electrocatalyst for hydrogenation of acetone to isopropanol as a potential energy carrier. The e-hydrogenation proceeds in water with quantitative FE and requires a theoretically minimal reduction potential of only +0.1 V; thus, simultaneously addressing all key challenges of ECH development.

As a widely utilized catalyst for transfer hydrogenation of organic carbonyls,¹ **1**'s corresponding metal hydride [(Cp*)Ir(bpy)(H)]⁺ (**3**) was initially expected to be the active intermediate in this process. We demonstrate that the acid stable [Ir-H]⁺ complex **3** can be electro-synthesized from **1** by simply applying a mild reduction potential in aqueous electrolyte, as confirmed by in situ UV/Vis- and ex situ NMR spectro-electrochemistry. Such straightforward access to acid-stable metal-hydrides is key for faraday-efficient electrocatalytic hydrogenation reactions and may lay the ground work of future systems. Contrasting literature precedent from transfer hydrogenation catalysis with **1**, we prove that there is no direct reaction between **3** and model substrate acetone in water at room temperature. Instead, we found that co-catalytic effects of carboxylic acids, in our case acetic acid, are necessary to foster a hydrogenation of acetone by **3** at room temperature. Through specific acid co-catalysis the reaction is mediated through simultaneously activating the substrate by H-bonding and the hydride by L-type ligand coordination in a metalacyclic intermediate (Figure 1). While electrocatalysis is well suited to detect such effects, their implications are highly relevant to the broad field of hydrogenation catalysis in general.

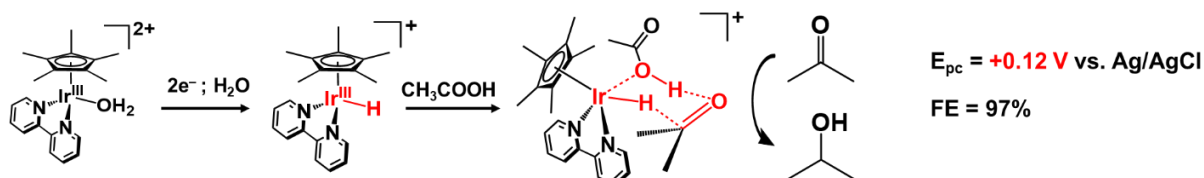


Figure 1: [(Cp*)Ir(bpy)(H)]⁺ (**3**) can be e-synthesized at mild potential and hydrogenate acetone with high FE of 97%, in a very energy efficient process enabled only by co-catalytic effects of acetic acid.

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Spectroscopy WithIn Fast Timescales (SWIFT): The new flagship XAS beamline coming to Diamond-II

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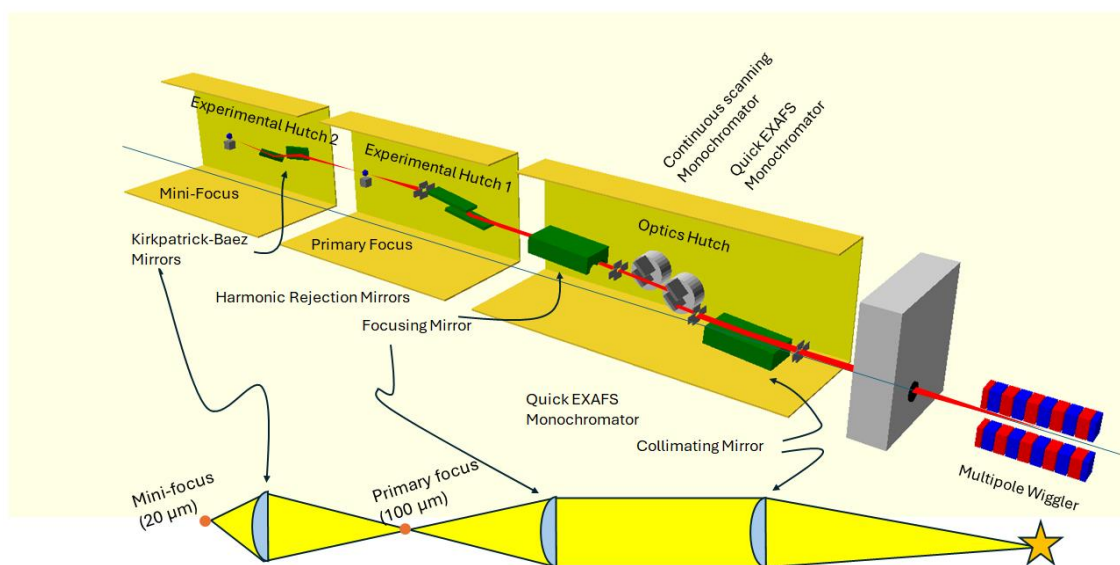
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SWIFT is a high flux core-level spectroscopy beamline with a design that strikes an impressive balance between time and spatial resolution, enabling processes to be followed on timescales of tenths of milliseconds and sample heterogeneities to be investigated down to 20 μm in scale. These features will enable science and engineering insights to be obtained that hitherto have been impractical to achieve, with economically important applications spanning manufacturing, energy, environmental management, chemical, aerospace and tourism. This new beamline will increase the relevance of XAS in these areas and will be of significant benefit to both academia and industry. SWIFT will contribute significantly to research in catalysis, batteries, nuclear materials, the environment, cultural heritage, enzymes, and will incorporate significant elements of AI and Big Data.

SWIFT is an essential development to maintain and enhance the capacity and capabilities for X-ray spectroscopy at Diamond-II, as the X-ray spectroscopy community will lose a beamline in the upgrade, and the core-EXAFS beamline (B18) is more than 3 times oversubscribed. However, the case for SWIFT is not only about capacity but also crucially about capability and being able to drive new research and innovation. The addition of SWIFT to the portfolio of X-ray Absorption Spectroscopy (XAS) instruments on Diamond-II will offer transformative capabilities for the study of materials in a wide range of disciplines including high flux, time resolution and ability to make spatially resolved measurements.

In short, SWIFT will be an essential piece of the research landscape and will be at the forefront of operando X-ray spectroscopy.



SWIFT beamline optical layout.

Synthesis and Reactivity of Soluble Cerium(IV)-oxo Clusters Towards Proton-Coupled Electron Transfer Reactions

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Cerium oxide (ceria) is a mixed-valence oxide containing both Ce^{4+} and Ce^{3+} ions, with its redox state ($\%\text{Ce}^{3+}$) varying in response to redox reactions. This behaviour is particularly pronounced at the nanoscale, where increased surface-to-bulk ratios stabilize Ce^{3+} sites, enhancing its redox flexibility. These properties make ceria a valuable catalyst, cocatalyst, and reducible oxide support. Ceria's redox activity primarily involves hydrogen or oxygen atom transfer, with thermochemistry playing a key role in its reactivity. At near-ambient temperatures or in colloidal suspensions, charge balance can be maintained via hydrogen atom binding. Reduction typically occurs through hydrogen atom addition ($\text{H}^\bullet \rightarrow \text{e}^- + \text{H}^+$), converting Ce^{4+} to Ce^{3+} and protonating an oxide site.^{1,2}

In this work, we synthesize solubilized cerium-oxo clusters, giving us the advantage of being able to use solution-based techniques, to probe the structure-reactivity relationships and kinetics of proton-coupled electron transfer reactions using various hydrogen-atom transfer reagents.

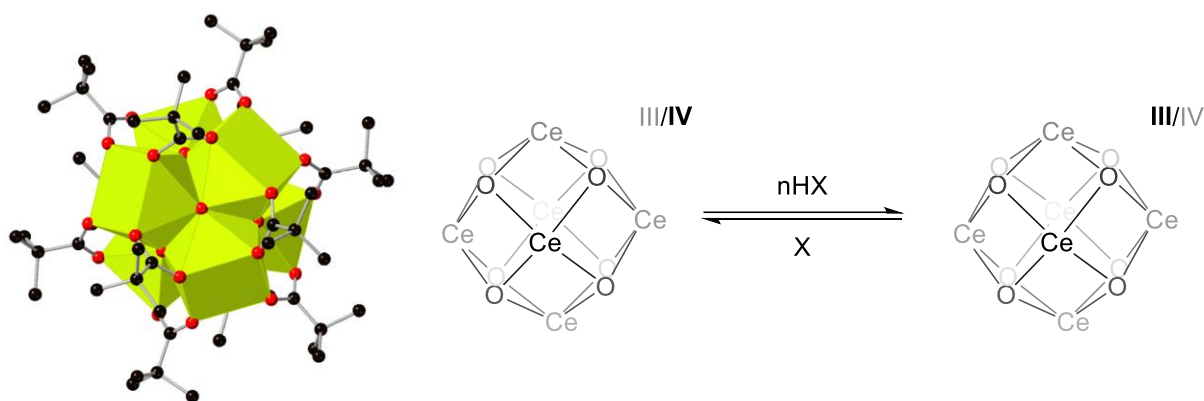


Figure 1: Single-crystal structure of a representative Cerium-Oxo Cluster ($[\text{Ce}_6(\text{O}_2\text{C}^t\text{Bu})_{12}(\text{O})_4(\text{OH})_4]$).

Figure 2.) Proton-Coupled electron transfer reaction of cerium-oxo clusters

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