Caltech
Student-Faculty Programs

Session D Abstracts

Composition optimization of an FeCoNiMo high-entropy alloy for hydrogen evolution
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High-entropy alloys of earth-abundant transition metals could replace platinum in hydrogen production by water splitting, but their compositional space is too large to search by experiment alone. This project optimized the molybdenum content of an iron-cobalt-nickel-molybdenum alloy on its close-packed (111) surface. Activity was judged by the Volmer step, in which water dissociates and leaves a hydrogen atom bound to the metal. DFT nudged elastic band calculations located the transition state along nine reaction paths. Grouped by the metal atom that receives the hydrogen, the barriers rise from nickel to cobalt to iron. They also follow the local arrangement around each site rather than the overall composition. A MACE interatomic potential fine-tuned on these calculations produced 100 equilibrated surfaces across 10 molybdenum concentrations, and a score built from the barriers ranked them. Activity peaks at 25% molybdenum. Below that value too little molybdenum reaches the surface to form sites, and above it molybdenum atoms sit next to one another and the sites are lost. Work continues on the Heyrovsky step, in which the bound hydrogen leaves as hydrogen gas.

Computational study of bimetallic MOF electrocatalysts for selective nitrogen reduction reaction
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Sustainable substitutes for the Haber-Bosch ammonia production pathway have been realized through the electrochemical nitrogen reduction reaction (eNRR). Practical selectivity of the eNRR is limited by N-N bond formation and the competing hydrogen evolution reaction (HER). This project uses computational density functional theory methods to analyze how bimetallic ordering within MOF-74 influences nitrogen adsorption and to assess activation and selectivity components. Initial screening analyzed a broad range of Fe-Mo/Fe-Ni structures and narrowed our focus to mixed and separated Fe-Mo arrangements. Adsorbate-framework arrangements and electronic energies were obtained through spin-polarized PBE-D3 calculations with a 500-eV plane-wave cutoff. Sites were named after their atomic order in VESTA structure files. Mixed Fe6 and Mo3 sites both retain end-on N2, while mixed Fe-Mo bridge and separated Fe sites relax to gas-like, desorbed states. On mixed structures, Fe and Mo show promise for selectivity and activation, respectively. Fe6 is electronically favorable for N2 adsorption by -0.40 eV, while H adsorption is unfavorable by +0.71 eV, making the site a leader in selectivity. Although Mo3 binds N2 more strongly (-1.36 eV) and shows that the N2 bond length increases after adsorption, a sign of activation, this site favors H adsorption, implying HER competition. Current results show electronic energy trends. Further work is needed to determine whether Fe selectivity or Mo activation governs eNRR performance.

Modelling the effects of tungsten alloying and surface oxidation on coverage-dependent hydrogen evolution in $Ni_{17}W_3$
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Electrolytic hydrogen offers a promising route to storing renewable energy, but current practice relies on platinum for the cathode reaction, whose cost and scarcity create a bottleneck to deployment at scale. Nickel-tungsten alloys are among the most promising non-precious replacements: nickel is abundant and already used in electrolysers, but binds hydrogen too strongly, and alloying with tungsten weakens that binding toward the Sabatier optimum. $Ni_{17}W_3$ is reported to reach 10 mA cm^{-2} at an overpotential of only 14 mV. Under operating conditions, however, the surface carries a substantial hydrogen coverage, and X-ray photoelectron spectra of the same material show tungsten in partially oxidised states alongside the metal. Here we use spin-polarised periodic DFT to build hydrogen coverage up site by site on pure Ni, on $Ni_{17}W_3$, and on $Ni_{17}W_3$ with two surface tungsten

atoms each bearing an oxo oxygen, enumerating the symmetry-inequivalent sites at every step rather than assuming a filling order. We find that alloying and oxidation act principally by removing adsorption sites: of the sixteen face-centred-cubic hollows on pure Ni, ten remain accessible on the alloy, and oxidation displaces the additional hydrogen out of the hollow sites entirely. Because each surface reaches thermoneutrality at its own coverage, the descriptor that distinguishes these catalysts is where saturation falls. Density of states, charge analysis, and constant-potential calculations characterise the electronic origin of this behaviour, and nudged elastic band calculations probe the kinetics of hydrogen recombination.

Development of a coarse-grained force field for perfluorononanoic acid (PFNA) micellization: From quantum mechanics and molecular dynamics to coarse-graining
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Per- and polyfluoroalkyl substances (PFAS), such as perfluorononanoic acid (PFNA), are highly persistent environmental pollutants that pose serious risks to public health and ecosystems. In aqueous environments, PFNA molecules self-assemble into micelles, a process that influences remediation strategies. A major challenge in computationally studying these systems is that standard force fields struggle to accurately describe the highly electronegative perfluorinated backbone. In this work, we aim to develop a multiscale computational model, transitioning from quantum mechanics (QM) and molecular dynamics (MD) to a coarse-grained (CG) force field, to investigate PFNA

micellization. Through a systematic QM analysis of the torsional energy landscape, our ongoing efforts focus on modifying atomistic force fields to better describe the molecule. Ultimately, we aim to develop a coarse-grained model for PFNA, enabling large-scale simulations of PFAS self-assembly and phase behavior.

Isolating and quantifying the pre-targeting complex of the GET pathway in *Aspergillus fumigatus*
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Aspergillus fumigatus is a deadly infectious fungus that has evolved resistance to existing antifungal drugs. Retro compounds have been shown to enhance the effectiveness of fungicides on drug-resistant fungi, making them promising candidates for combating antimicrobial resistance. Retro compounds in human cell lines inhibit retrograde transport in a non-cytotoxic manner by disrupting the Guided Entry of Tail-anchored proteins (GET) pathway, which transports tail-anchored proteins to the endoplasmic reticulum. Specifically, Retro compounds lock the pre-targeting complex of human Get3/4 and Bag6 in a stable conformation that prohibits tail-anchors from being transferred to the main chaperone on the GET pathway, Get3. Retro compounds have also been demonstrated to interact with the *A. fumigatus* Get3, however, the mechanism of action of Retro compounds on the fungal GET pathway is undetermined. If the mechanism of action is conserved across eukaryotes, the inhibition of retrograde transport in filamentous fungi could provide a novel, potent target for antimicrobial therapeutic development. Thus, we purified *Af*Get3 and *Af*Get4/5 to better understand the *A. fumigatus* pre-targeting complex and aim to quantify the effect of Retro compounds on the fungal GET pathway

Designing a gas cell for the first ultrafast all-electron spectrometer
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Mentors: Scott K. Cushing and Bethany De Roulet

In this research project, a gas cell was designed and fabricated for an ultrafast all-electron spectrometer that can measure electrochemical processes in a gaseous state, such as CO2 reduction reaction (CO2RR). There is currently no method of measuring the intermediates in electron initiated electrochemical processes, which are integral to both further understanding these processes and optimizing materials used in the reactions. An ultrafast all-electron spectrometer will be able to

measure this by giving picosecond temporal resolution to instruments at low <10 eV energies. This gas cell has been designed and fabricated, and will be tested under 20 Torr of pressure. The gas cell will also be tested inside the experimental set up with the copper cathode mounted, the CO2 running through the inlet and outlet lines, and the laser running through the cell.

Molecular characterization of mRNA quality control in humans
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Mentor: Isaac Fianu

RNA polymerase II (Pol II) transcription is coordinated with RNA processing and quality-control mechanisms that regulate transcript stability and transcription termination. Decapping protein 2 (DCP2) removes the 7-methylguanosine cap from RNA, generating a 5′-monophosphorylated RNA substrate that can be degraded by 5′→3′ exoribonucleases [PMID: 21935889]. Although primarily associated with cytoplasmic mRNA decay, DCP2 has also been implicated in nuclear RNA quality control and premature Pol II transcription termination [PMID: 14749774; PMID: 22483619]. Previous cellular studies suggest that DCP2 may coordinate with the 5′→3′ exoribonuclease XRN2, potentially coupling RNA decapping and degradation to transcription termination; however, the biochemical basis of this relationship remains unclear.

This study aims to define the functional relationship between DCP2 and XRN2 using purified recombinant proteins and biochemical approaches. Preliminary pull-down assays examining XRN2 and the DCP2 cofactor DCP1A showed no detectable direct interaction under the conditions tested. Recombinant human DCP2 has since been successfully expressed and purified, enabling direct investigation of DCP2–XRN2 coordination. Ongoing studies will use pull-down assays to test complex formation and decapping and RNA degradation assays to determine whether DCP2 activity facilitates XRN2-dependent RNA degradation.

Synthesis and characterization of transition metal complexes for molecular qubit applications
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Mentors: Theodor Agapie and Fernando Guerrero

The field of quantum information science leverages quantum mechanical phenomena, such as superposition and entanglement, to advance computing and sensing. The basic unit of quantum information is the quantum bit, or "qubit," which can exist in a superposition of both the 0 and 1 state. The extreme sensitivity of qubits may enable detection of vanishingly small changes in the local environment, a property applicable to molecular sensing. Towards this goal, molecular platforms, including open shell transition metal complexes (spin = ½), have garnered interest for their potential to produce measurable changes in spin relaxation behavior when exposed to environmental stimuli. Previous efforts in the Agapie Group have demonstrated how perturbations at or near the spin center are transduced into detectable changes in the electronic structure of a molecular qubit. Recent work expands this platform in two directions. Through the formation of crown-ether-functionalized copper qubits, the effects of cation binding on spin lattice relaxation has been explored. In parallel, a new sensing modality has been investigated using novel vanadium(IV) complexes supported by a *bis*-triazinyl bipyridine scaffold. Ongoing efforts target installation of variable ligands in the equatorial plane of these vanadyl qubit candidates, expanding understanding of the sensitivity of transition metal complexes.

Synthesis and characterization of a trimetallic MNi_2 complex for CO_2 reduction
Anna L. Liu
Mentors: Theodor Agapie and Nicole Piekut

Multimetallic catalysts enable enhanced or divergent reactivity from traditional monometallic catalysts owing to cooperative interactions between metal centers, with applications in small molecule activation and organic transformations. Here, we report progress towards synthesizing a trimetallic MNi_2 complex (M = Ti, Zr, Mo) stabilized by a rigid, planar, tetradentate bis-triazinyl bipyridine (BTBP) ligand. This system integrates late-late and early-late transition metal interactions for merged

advantages including multiple metal-metal interactions to tune reactivity, multiple redox active centers to store electrons, and multiple metal sites for substrate binding. As such, we anticipate this unique structure to be well suited for CO_2 reduction. The BTBP ligand was synthesized and metalated with various titanium sources; precursors containing other metals (M = Zr, Mo) were also investigated. Nuclear magnetic resonance (NMR) characterization suggests that $TiCl_3$ and $Ti(N\mathit{t}Bu)Cl_2(py)_3$ successfully metalated the BTBP ligand, and further single-crystal X-ray diffraction (XRD) studies will be conducted to confirm the structures. Subsequently, nickel will be added to the M-BTBP complexes, screening different conditions and nickel sources. The geometric and electronic structure of the final MNi_2 complex will be probed with single-crystal XRD, NMR, X-ray absorption spectroscopy, and computational studies. Finally, the aptitude of these complexes for CO_2 reduction will be studied.

Investigating the characteristics of puncta formed by PPARγ

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Peroxisome proliferator-activated receptor gamma (PPARγ) is a transcription factor (TF) that regulates expression of genes that affect adipogenesis and lipid metabolism. Previous studies established PPARγ form puncta at peroxisome proliferator response elements through homotypic interactions of intrinsically disordered regions. PPARγ is endogenously activated by a fatty acid which promotes its change into an active AF-2 confirmation allowing it recruit other coactivators and form a heterodimer with retinoid X receptor to promote transcription. We aim to study how the activation of PPARγ affects puncta formation. We used rosiglitazone, a strong agonist, to activate PPARγ in cells. We found that activated wild-type PPARγ resulted in larger puncta and partition coefficients as compared to inactive PPARγ. An inactive mutant of PPARγ, PPARγ-Y501F, displayed a lower amount of condensate formation pre-activation; once activated, there was a less significant increase in condensate size and partition coefficient as compared to wild-type PPARγ. These findings show that post-PPARγ activation, the ligand-responsive AF-2 region contributes to the remodeling of condensates and enlarges them through the recruitment of other PPARγ molecules and coactivators. Future work can explore the relationship between PPARγ condensate size and transcription levels.