To my beloved parents, grandparents and lifelong friends
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<td>Adiabatic Longitudinal Transport After Dissociation Engenders Net Alignment</td>
</tr>
<tr>
<td>BET</td>
<td>Brunauer-Emmett-Teller</td>
</tr>
<tr>
<td>dDNP</td>
<td>Dissolution-Dynamic Nuclear Polarization</td>
</tr>
<tr>
<td>DFT</td>
<td>Density Functional Theory</td>
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<tr>
<td>DMAC</td>
<td>Dimethyl Acetylene Dicarboxylate</td>
</tr>
<tr>
<td>DMF</td>
<td>Dimethyl Fumarate</td>
</tr>
<tr>
<td>DMM</td>
<td>Dimethyl Maleate</td>
</tr>
<tr>
<td>DMS</td>
<td>Dimethyl Succinate</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy-dispersive X-ray Spectroscopy</td>
</tr>
<tr>
<td>EF</td>
<td>Enhancement Factor</td>
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<tr>
<td>FAT</td>
<td>Fixed Analyzer Transmission</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>FID</td>
<td>Free-induction Decay</td>
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<tr>
<td>HAADF-STEM</td>
<td>High Angle Annular Dark Field-Scanning Transmission Electron Microscopy</td>
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<tr>
<td>HEA</td>
<td>2-hydroxyethyl Acrylate</td>
</tr>
<tr>
<td>HEP</td>
<td>2-hydroxyethyl Propionate</td>
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<tr>
<td>HetPHIP</td>
<td>Parahydrogen Induced Polarization by Heterogeneous Catalysis</td>
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<tr>
<td>HP</td>
<td>Hyperpolarized</td>
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<tr>
<td>HRTEM</td>
<td>High Resolution Transmission Electron Microscopy</td>
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<tr>
<td>ICP-MS</td>
<td>Inductively Coupled Plasma-Mass Spectrometry</td>
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<tr>
<td>iNPs</td>
<td>Intermetallic Nanoparticles</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<tr>
<td>mSiO₂</td>
<td>Mesoporous Silica</td>
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n-H₂ Normal Hydrogen with Approximately 25% Parahydrogen
NMR Nuclear Magnetic Resonance
NPs Nanoparticles
o.d. Outer Diameter
o-H₂ Orthohydrogen
PA Propane
PASADENA Parahydrogen and Synthesis Allows Drastically Enhanced Nuclear Alignment
PD Propadiene
PE Propene
p-H₂ Parahydrogen
PHIP Parahydrogen Induced Polarization
ppb Parts per billion
ppm Parts per Million
PR Pairwise Replacement
Pt@mSiO₂ Mesoporous Silica Encapsulated Pt Nanoparticles
Pt₃Sn@mSiO₂ Mesoporous Silica Encapsulated Pt-Sn Intermetallic Nanoparticles with an Atomic Ratio of 3
PtSn@mSiO₂ Mesoporous Silica Encapsulated Pt-Sn Intermetallic Nanoparticles with an Atomic Ratio of 1
PXRD Powder X-ray Diffraction
PY Propyne
RF Radio Frequency
SABRE Signal Amplification by Reversible Exchange
SIMPLE Surface Induced Magnetic Polarization by Ligand Exchange
SLIC Spin Locking Induced Crossing
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<td>SMSI</td>
<td>Strong Metal-Support Interaction</td>
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<td>STEM</td>
<td>Scanning Transmission Electron Microscopy</td>
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<tr>
<td>STEM-ABF</td>
<td>Scanning Transmission Electron Microscopy- annular bright field</td>
</tr>
<tr>
<td>SWAMP</td>
<td>Surface Waters Acquires Magnetized Protons</td>
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<td>TCA</td>
<td>Tricarboxylic Acid</td>
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<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
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<tr>
<td>TEOS</td>
<td>Tetraethylorthosilicate</td>
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<td>TPD</td>
<td>Temperature Programed Desorption</td>
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PARAHYDROGEN INDUCED POLARIZATION BY HETEROGENEOUS CATALYSIS

By
Evan Wenbo Zhao

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Chair: Clifford Russ Bowers
Major: Chemistry

Parahydrogen Induced Polarization (PHIP) is a simple and inexpensive technique that enhances the NMR sensitivity by orders of magnitude. The signal enhancement enables efficient metabolomics, early cancer detection and monitoring of chemical processes in operando by magnetic resonance imaging. A key requirement for achieving the PHIP NMR signal enhancement is the preservation of the spin order of parahydrogen on the adduct molecules after a hydrogenation reaction. The protons are added in a pairwise fashion in which the two added protons originate from the same dihydrogen molecule. A major portion of this thesis focuses on improving the percentage of pairwise addition by investigating the surface chemistry over various catalyst materials. Using a mesoporous silica-encapsulated Pt-Sn intermetallic nanoparticle catalyst, a record-high NMR signal enhancement and the aqueous phase PHIP signal are demonstrated. Long-lived dimethyl maleate with a spin relaxation time of 196 s was produced. Facet-dependence of pairwise addition over ceria nanorods, cubes and octahedra are unveiled. Over iridium nanoparticles supported on titanium oxide, the strong metal-support interaction induced after high-temperature treatment was found to increase the percentage of pairwise addition.
In the last part of this thesis, the discovery of a simple, readily scalable, and inexpensive method for orienting the proton magnetic moments in water molecules is reported, resulting in nuclear magnetic resonant (NMR) signal enhancements of up to 40 compared to normal water at 9.4 T. By simply bubbling 50% para-enriched hydrogen gas through a volume of liquid water containing an insoluble silica-protected Pt-Sn alloy nanoparticle catalyst, contaminant-free hyperpolarized water can be produced in a matter of seconds, and intense stimulated radio wave emission signals are detected in the proton nuclear magnetic resonance spectrum. Different from the conventional PHIP effect arises from the pairwise addition chemistry, this effect is due to the symmetry breaking hydrogen chemisorption combined with a single H atom exchange. This is the first demonstration of water NMR signal enhancement derived from parahydrogen. Hyperpolarized methanol and ethanol can also be hyperpolarized using the same catalyst. In principle, MRI scan times can be drastically reduced by this approach.
CHAPTER 1
INTRODUCTION

Outline

This thesis is organized in the following manner. Chapter 1 presents a general introduction of the parahydrogen induced polarization (PHIP) effect with the emphasis on heterogenous hydrogenation catalysis, followed by the fundamental theories of the PHIP effect in Chapter 2 and the instrumentation that was built and is being constructed to perform PHIP experiments in gaseous and liquid phases in Chapter 3. Chapter 4, 5, and 6 present the PHIP studies over Pt-Sn intermetallic nanoparticles, shaped ceria nanocrystals and metal oxide supported Ir nanoparticles, respectively. Chapter 7 presents a newly discovered phenomenon Surface Waters Acquires Magnetized Protons (SWAMP).

Hyperpolarization: Enhancement of NMR Sensitivity

Ever since the first detection of NMR signal from paraffin wax by Purcell, Torrey and Pound in 1945, there has been rigorous development of NMR spectroscopy. The variation of NMR, magnetic resonance imaging (MRI) has become an essential tool for biomedical diagnosis. However, NMR is known as an insensitive technique due to the low-energy induced resonance by radio frequency wave. Through external perturbation of the spin populations, hyperpolarization (HP) is a technique that drastically enhances the NMR sensitivity through either physical or chemical approaches, broadening the applicability of NMR in almost all branches of science. In the biomedical field, attributed to the signal enhancement afforded by one of the HP techniques, dynamic nuclear polarization, early detection of prostate cancer has been successfully demonstrated in
human trials. Among all the HP techniques, Parahydrogen Induced Polarization (PHIP) is the most inexpensive and arguably the most promising. Recent breakthroughs in the PHIP methodology have led to its emergence as a viable alternative with greater simplicity, speed, and scalability to dissolution-Dynamic Nuclear Polarization (the current dominant hyperpolarization technique) for hyperpolarized biomolecular magnetic resonance imaging (MRI). The transformation of the pure two-spin singlet spin order inherent to the protons in parahydrogen (p-H₂) into NMR-observable nuclear spin Zeeman order is facilitated by hydrogenation catalysis. The rapidly growing list of contrast agents that have been demonstrated to be hyperpolarized by the hydrogenative mode of PHIP includes acetate and pyruvate, lactate and phospholactate, nicotinimide, succinate etc.

Heterogeneous hydrogenation catalysis by pairwise addition of p-H₂ over supported metal catalysts offers rapid, continuous-flow production of catalyst-free HP hydrogenation adducts. However, the comparatively low HP levels (c.a. 2-3% for TiO₂-supported Pt) and the restriction mainly to gases and vapors of volatile compounds are non-trivial challenges of PHIP via heterogeneous catalysis. Moreover, the spin relaxation time of the hyperpolarized signal is commonly within a minute, limiting its applications in biological processes only on a short timescale. To address these challenges, a part of my Ph.D. research focuses on (1) improving the HP levels of PHIP technique; (2) broadening the scope of hyperpolarizable molecules; (3) prolonging the spin relaxation time of HP molecules through the understanding of fundamental catalytic processes, rational design of nanomaterials, instrumentation development and the understanding of the underlining spin dynamics.
Applications of Parahydrogen Induced Polarization

Mechanistic Probe of Catalysis

PHIP was first demonstrated using homogeneous Wilkinson’s catalyst. Ever since then, it has been used as a mechanistic probe to detect reaction intermediates, e.g. metal hydrides, and reveal reaction mechanisms over homogeneous catalysts, including Ir, Rh and Co metal complexes. In 2008, Koptyug et al. reported the observation of PHIP effect over alumina supported platinum nanoparticles. The effect was dubbed “HetPHIP” because of the heterogeneous nature of the catalyst. The observation itself serves as an evidence that a fraction of the adduct molecules were produced through the pairwise addition path, i.e. the two added protons originate from the same dihydrogen molecule. HetPHIP is the only available experimental tool that provides the information about pairwise addition and thus being used as a mechanistic probe in heterogeneous catalysis over the past decade.

Imaging of Catalytic Reactions in Operando

Because of the sensitivity gain afforded by and the catalytically induced nature of PHIP, it has been applied in MRI of hydrogenation reaction in operando. Information inside an operating reactor, such as spatial distribution of product, flow and local thermal heating can be acquired. The direct visualization of these parameters facilitates the design and optimization of chemical reactors.

Production of Hyperpolarized Contrast Agents and Metabolites under MRI

Angiography of a guinea pig head and a rat thorax with HP hydroxyethylpropionate prepared by hydrogenation of hydroxyethylacrylate was demonstrated. Upon hydrogenation of sodium 1-13C acetylenedicarboxylate, HP 13C succinate was produced as a diagnostic agent to identify brain tumor ex vivo. HP 13C
diethyl succinate was produced upon hydrogenation of $^{13}$C diethyl fumarate, enabling the real-time molecular imaging of tricarboxylic acid cycle (TCA) in vivo.\textsuperscript{9} 

**Development of Efficient Heterogeneous Catalysts**

Compared to its homogeneous counterparts, heterogeneous catalysts have the advantages of easy and fast separation from product mixture, compatibility with continuous-flow production of hyperpolarized molecules. However, because of the rapid diffusion of the adsorbed hydrogen atoms on a vast solid surface and the loss of spin order of p-H\textsubscript{2}, the polarization level is only a few percent of the theoretical value.\textsuperscript{30} Since the observation of HetPHIP, a new catalytic concept pairwise selectivity came into birth.\textsuperscript{5} It is defined as the ratio of the number of added protons in a pairwise fashion and the total added protons. Extensive efforts have been devoted to the search of heterogeneous catalysts that provide a high pairwise selectivity and conversion. Thorough reviews of these endeavors from different research groups are provided in the Backgrounds of Chapter 4, 5 and 6.

Metal oxide supported metal nanoparticles represent a large family of heterogeneous catalysts for hydrogenation reactions. Combinations of different supports, including Si\textsubscript{2}O, Al\textsubscript{2}O\textsubscript{3} and TiO\textsubscript{2} and group VIII metal nanoparticles, including Pt, Pd, Au and Rh have been studied in the context of HetPHIP.\textsuperscript{5, 31-33} Strong metal-support interaction (SMSI) was found to have significant effect on the pairwise selectivity. SMSI is a well-known effect that exists in reducible metal oxide supported nanoparticles.\textsuperscript{34-35} While it enhances the pairwise selectivity over supported Pt nanoparticles,\textsuperscript{31} SMSI suppresses the pairwise selectivity over supported Pd nanoparticles.\textsuperscript{32} The fundamental reason is still not clear. Not until recently, most HetPHIP studies focus on gas-phase reactions in which reaction parameters can be
precisely controlled for quantitative studies, however, not suitable for producing non-volatile HP metabolite for clinical MRI applications.

Colloidal Pt nanoparticles in aqueous phase have been used to produce one of the HP MRI contrast agents, hydroxyethyl propionate upon hydrogenation of hydroxyethyl acrylate.\textsuperscript{36-37} However, the pairwise selectivity is below 1%. It takes tens of minutes of centrifugation to separate the catalysts from the product mixture, results in complete loss of hyperpolarization due to T$_1$ relaxation which is on the timescale of seconds. Therefore, the advantage of heterogeneity is lost in terms of producing catalyst-free HP molecules.

Single-atom heterogeneous catalyst is an appealing candidate because of its structural similarity to homogenous catalyst in which a single metal center is expected to ensure the pairwise addition. However, stabilization of single-atom catalyst is challenging. In contrast to homogeneous catalysts which are coordinated to organic ligands, single-atom catalysts are supported on solid materials and thus bear the risks of H spillover to the support and loss of spin order. Hydrogenation of 1,3-butadiene and 1-butyne with p-H$_2$ was catalyzed by a monoatomic gold catalyst dispersed on multiwall carbon nanotubes.\textsuperscript{38} PHIP signal enhancement was observed on the product molecules. However, the total conversion of the reaction is too low to acquire a thermally polarized signal for quantification of PHIP enhancement factors.

Despite the extensive efforts in the past decade, a heterogeneous catalyst that produces high polarization level and total conversion is yet to be discovered.
Spin Isomers of Hydrogen Molecules

According to the Pauli Exclusion Principle, two identical fermions which possess $\frac{1}{2}$ spins, the total wave function must be anti-symmetric with respect to permutation of nuclear state. According to Born-Oppenheimer approximation, the total wave function of dihydrogen molecule can be factorized into electronic, vibrational, rotational and nuclear wave functions,

$$\Psi_{\text{total}} = \Psi_e \Psi_v \Psi_r \Psi_n$$  \hspace{1cm} (2-1)

The ground electronic wave function is symmetric with respect to the inversion and reflection of the electronic coordinates. The vibrational wave function is symmetric because of the linearity of the diatomic molecule. Therefore, the rational and nuclear wave functions are coupled. To fulfill the anti-symmetry of the total wave function, a symmetric rotational state (with even rotational quantum number $J$) leads to an anti-symmetric nuclear state with the total angular momenta of zero, named para-hydrogen ($p$-H$_2$). An anti-symmetric rotational state (with odd rotational quantum number $J$) leads to a symmetric nuclear state with the total angular momenta of one, named ortho-para-hydrogen ($o$-H$_2$).

$$|\Psi_{o-H_2}\rangle = \frac{1}{\sqrt{2}}(|\alpha\beta\rangle + |\beta\alpha\rangle)$$

$$|\Psi_{p-H_2}\rangle = \frac{1}{\sqrt{2}}(|\alpha\beta\rangle - |\beta\alpha\rangle)$$  \hspace{1cm} (2-2)
As seen in Eq. (2-2), the ground rotational state of o-H$_2$ is degenerated to a triplet and p-H$_2$ is a singlet. The energy difference is 15 meV or 170.6 K.

The composition of p-H$_2$ and o-H$_2$ can be derived from the rigid rotor partition function,

$$\frac{N_{o-H_2}}{N_{p-H_2}} = \frac{3 \sum_{j=1,3,5,...} (2j+1)e^{-\Theta_r,j(j+1)/T}}{\sum_{j=0,2,4,...} (2j+1)e^{-\Theta_r,j(j+1)/T}} (2-3)$$

$\Theta_r$ is the characteristic temperature of H$_2$ rotation and $\Theta_r = \hbar^2 / 2kA$, $A = \mu r^2$ is the moment of inertia for the internuclear distance $r$. $\mu = m_1m_2 / (m_1 + m_2)$ is the reduced mass of the dihydrogen molecule. Therefore, $\Theta_r = 85.3K$. Figure 2-1 presents the fraction of p-H$_2$ as a function of temperature. At 77 K which is accessible by liquid nitrogen, there is 51% p-H$_2$. At 25 K, there is 99% p-H$_2$. The interconversion of p-o H$_2$ is magnetic dipole forbidden, which makes them quasi-stable. Without external perturbation, it takes months to reach thermal equilibrium. The quasi-stability affords the playground for applications that are related to p-H$_2$.

Figure 2-1. Fraction of p-H$_2$ at equilibrium as a function of temperature.
The density matrix in the singlet-triplet basis as defined in (2-2) is,

\[
\rho_{H_2} = \begin{pmatrix}
\psi_{1,1} & (1 - \chi_p) / 3 & 0 & 0 & 0 \\
\psi_{1,0} & 0 & (1 - \chi_p) / 3 & 0 & 0 \\
\psi_{1,-1} & 0 & 0 & (1 - \chi_p) / 3 & 0 \\
\psi_{0,0} & 0 & 0 & 0 & \chi_p \\
\end{pmatrix}
\]

(2-4)

\(\chi_p\) is the mole fraction of p-H\(_2\). Therefore, the equilibrium density operator of the para-ortho hydrogen mixture can be written as,

\[
\hat{\rho}_{H_2} = \frac{1}{4} \hat{I}_1 \cdot \hat{I}_2
\]

(2-5)

and

\[
f = (4\chi_p - 1) / 3
\]

(2-6)

\(\hat{I}_1\) and \(\hat{I}_2\) are the angular momentum operators for the two protons, respectively.

Parahydrogen and Synthesis Allows Drastically Enhanced Nuclear Alignment (PASADENA)

When p-H\(_2\) are added to an unsaturated organic substrate via chemical reactions in a pairwise fashion and the two proton sites on the adduct molecule are chemically inequivalent, PASADENA happens.\(^2\) The eigenstates are,

\[
\begin{align*}
|1\rangle &= |\alpha\alpha\rangle \\
|2\rangle &= c_1|\alpha\beta\rangle + c_2|\beta\alpha\rangle \\
|3\rangle &= -c_2|\alpha\beta\rangle + c_1|\beta\alpha\rangle \\
|4\rangle &= |\beta\beta\rangle
\end{align*}
\]

(2-7)

\(c_1\) and \(c_2\) are defined as,

\[
\begin{align*}
c_1 &= \cos(\kappa / 2) \\
c_2 &= \sin(\kappa / 2)
\end{align*}
\]

(2-8)

\[\tan(\kappa) = J / \Delta \omega_z\]
So $\kappa$ defines the relative coupling strength $J$ with respect to the chemical shift difference of the two protons ($\Delta \omega_z = \omega_{z1} - \omega_{z2}$) in liquid and gas where dipolar coupling is averaged to zero. At high magnetic field where $\Delta \omega_z \gg J$, $|2\rangle$ and $|3\rangle$ become $|\alpha\beta\rangle$ and $|\beta\alpha\rangle$.

The Hamiltonian for the two protons in the rotating frame is,

$$H = \omega_{z1} \hat{I}_{z1} + \omega_{z2} \hat{I}_{z2} + J \hat{I}_1 \cdot \hat{I}_2$$ \hspace{1cm} (2-9)

Upon pairwise addition, the Hamiltonian of the two protons changes instantaneously. Based on sudden approximation,\(^{40}\) the projection of the density operator of the hydrogen molecules in the singlet-triplet basis onto the Zeeman basis at high magnetic field ($\kappa \equiv 0$) is,

$$\rho_{\text{adduct}} = \begin{bmatrix} |\beta\beta\rangle & (1 - f)/4 & 0 & 0 & 0 \\ |\alpha\beta\rangle & 0 & (1 + f)/4 & -f/2 & 0 \\ |\beta\alpha\rangle & 0 & -f/2 & (1 + f)/4 & 0 \\ |\alpha\alpha\rangle & 0 & 0 & 0 & (1 - f)/4 \end{bmatrix}$$ \hspace{1cm} (2-10)

When there is 100% p-H\(_2\), i.e. $f = 1$, $\rho_{\text{adduct}}^{\text{PASADENA}}$ becomes,

$$\rho_{\text{adduct}}^{\text{PASADENA}} = \begin{bmatrix} |\beta\beta\rangle & 0 & 0 & 0 \\ |\alpha\beta\rangle & 0 & 1/2 & -1/2 & 0 \\ |\beta\alpha\rangle & 0 & -1/2 & 1/2 & 0 \\ |\alpha\alpha\rangle & 0 & 0 & 0 & 0 \end{bmatrix}$$ \hspace{1cm} (2-11)

Therefore, the density operator $\hat{\rho}_{\text{adduct}}^{\text{PASADENA}}$,

$$\hat{\rho}_{\text{adduct}}^{\text{PASADENA}} = \hat{\rho}_{\text{H}_2}$$ \hspace{1cm} (2-12)

Figure 2-2 presents the quantum mechanical picture of symmetry breaking p-H\(_2\) addition at high field. As a result of the density matrix of the adduct molecule (2-11), the
population in the singlet state is transferred to the $|\alpha\beta\rangle$ and $|\beta\alpha\rangle$ evenly. Upon radio frequency irradiation, stimulated absorption give rise to peak 2 and 4 while stimulated emission give rise to peak 1 and 3. The off-diagonal elements which represent the coherence between $|\alpha\beta\rangle$ and $|\beta\alpha\rangle$ is averaged to zero if the reaction lasts longer than the coherent time macroscopically. Because of the term $\hat{I}_{1z} \cdot \hat{I}_{2z}$ in the density operator, a $\pi / 4$ pulse gives the strongest signal intensity.

Adiabatic Longitudinal Transport After Dissociation Engenders Net Alignment (ALTADENA)

In PASADENA, hydrogenation happens at high magnetic field and thus the eigenstates of the two protons change instantaneously from singlet-triplet to Zeeman states. In ALTADENA, hydrogenation happens at low magnetic field in the strong coupling regime of the two protons, i.e. $J \gg \Delta \omega_z$ $^4$. Therefore, the singlet-triplet states remain the eigenstates of the two protons on the adduct molecule. As presented in
Figure 2-3, The energy difference between the singlet and triple states collapse to the \( J \) coupling. The adiabatic transport (a smooth evolution of the singlet-triplet into the Zeeman states when the transport is adequately slow) of the adduct molecule to the high magnetic field preserve the population in the final state 1) \( |\beta\alpha\rangle \) when \( J \) and \( \Delta\omega_z \) are of the same sign; 2) \( |\alpha\beta\rangle \) when \( J \) and \( \Delta\omega_z \) are of the different signs, following Eq. (2-7) and (2-8).

Figure 2-3. ALTADENA energy correlation diagram with \( J \) and \( \Delta\omega_z \) of the same sign.

The density matrix of \( \rho_{\text{adduct}}^{\text{ALTADENA}} \) becomes,

\[
\rho_{\text{adduct}}^{\text{ALTADENA}} = \begin{pmatrix}
|\beta\beta\rangle & |\beta\alpha\rangle & |\alpha\beta\rangle & |\alpha\alpha\rangle \\
1/4 - f/4 & 1/4 - f/4 & 1/4 + 3f/4 & 1/4 - f/4 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

(2-13)

When there is 100% p-H\(_2\), i.e. \( f = 1 \), \( \rho_{\text{adduct}}^{\text{ALTADENA}} \) becomes,
\[
\rho_{\text{ALTADENA adduct}} = \begin{bmatrix}
\beta\beta & 0 & 0 & 0 \\
\alpha\beta & 0 & 0 & 0 \\
\beta\alpha & 0 & 0 & 1 \\
\alpha\alpha & 0 & 0 & 0 
\end{bmatrix}
\]  

(2-14)

Therefore, the density operator \( \hat{\rho}_{\text{adduct}} \) can be written as,

\[
\hat{\rho}_{\text{adduct}}^{\text{ALTADENA}} = \frac{1}{4} - f \left[ \hat{I}_{1z} \cdot \hat{I}_{2z} \pm 1 \right] / 2(\hat{I}_{1z} - \hat{I}_{2z})
\]  

(2-15)

The pulse is optimized at \( \frac{\pi}{2} \) for ALTADENA because of the \((\hat{I}_{1z} - \hat{I}_{2z})\) term in the density operator.

**Calculations of PHIP Enhancement Factor and Pairwise Selectivity**

**Experimental Signal Enhancement Factor**

The experimental signal enhancement factors \( \eta^{\text{exp}} \) were calculated as the ratio of the multiplet signal integrals of the PHIP and thermally polarized protons of the hyperpolarized molecules

\[
\eta^{\text{exp}} = \frac{C^{\text{PHIP}} S^{\text{PHIP}} / N^{\text{PHIP}}}{(S^{\text{thermal}} / m) / N^{\text{thermal}}}
\]  

(2-16)

**Table 2-1. Symbols of parameters in Eq. (2-16)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>( S^{\text{PHIP}} )</td>
<td>Integrated ALTADENA signal of adduct formed by reaction with p-H2</td>
</tr>
<tr>
<td>( S^{\text{thermal}} )</td>
<td>Integrated thermally polarized signal of adduct after full relaxation of HP signal</td>
</tr>
<tr>
<td>( C^{\text{PHIP}} )</td>
<td>Relaxation correction for losses during transport from the reactor to the NMR detection coil</td>
</tr>
<tr>
<td>( m )</td>
<td>Number of protons in a magnetically equivalent set</td>
</tr>
<tr>
<td>( N^{\text{PHIP}} )</td>
<td>Number of transients accumulated for acquisition of the ALTADENA</td>
</tr>
<tr>
<td>( N^{\text{thermal}} )</td>
<td>Number of transients accumulated for acquisition of the thermally polarized signal</td>
</tr>
</tbody>
</table>
**Theoretical Signal Enhancement Factor**

The Zeeman order for two initial conditions prepared from i) thermal equilibrium and ii) addition of p-H$_2$ followed by adiabatic transport to high field.

Starting with the density operator for $n$ protons at thermal equilibrium,

$$\hat{\rho}^{\text{thermal}} = \frac{\exp[-\hat{H} / (k_B T)]}{\text{Tr} \{ \exp[-\hat{H} / (k_B T)] \}} \quad (2-17)$$

Where

$$\hat{H} = \hat{H}_0 + \hat{H}_{\text{int}} \quad (2-18)$$

$$\hat{H}_0 = -\gamma B_0 \hat{I}_z \quad (2-19)$$

$\hat{H}_{\text{int}}$ is the (rotating frame) internal Hamiltonian and,

$$\hat{I}_z = \sum_{i=1}^{n} \hat{I}_{z,i} \quad (2-20)$$

In the high field, according to high-temperature approximation,

$$\hat{\rho}^{\text{thermal}} \approx 2^{-n}(\hat{1} - \hbar \beta \omega_0 \hat{I}_z) \quad (2-21)$$

The NMR signal of any proton derived from its Zeeman order,

$$S^{\text{thermal}} \propto \langle \hat{I}_z \rangle = \text{Tr} \{ \hat{I}_z \cdot \hat{\rho}^{\text{thermal}} \} = \frac{\hbar |\omega_0|}{4k_B T} \quad (2-22)$$

For propene (PE) hydrogenation at low magnetic field, C$_3$H$_6$ + H$_2$ → C$_3$H$_8$, the sharing of the spin order within the propane (PA) molecule is negligible. The final density operator of a two-spin system at high field in the ALTADENA mode is given by (2-15). When a $\pi / 2$ pulse is applied, only the Zeeman order contributes to the NMR signal.
The theoretical enhancement factor for a proton is,

$$|\eta_{PA}^{\text{theor}}| = \frac{|S_{\text{ALTADENA}}^2|}{S_{\text{thermal}}} = \frac{2fk_BT}{\hbar|\omega_0|}$$  

(2-24)

Table 2-2. Symbols of parameters in Eq. (2-24)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>$f$</td>
<td>Defined in Eq. (2-6)</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Bolzmann constant</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature in K</td>
</tr>
<tr>
<td>$\hbar$</td>
<td>Plank constant</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>Larmor frequency in laboratory frame in radians</td>
</tr>
</tbody>
</table>

At 300 K and 9.4 T and with 50% p-H$_2$, $|\eta_{PA}^{\text{theor}}| = 10418$.

For propyne (PY) hydrogenation at low magnetic field, C$_3$H$_4$ + H$_2$ → C$_3$H$_6$, the sharing of the spin order happens within the J-coupling network of propene (PE). The effect of sharing is different for the cis and trans dispositions of scalar order. The results of the numerical density matrix simulation of $\langle \hat{I}_{zi} \rangle$ for each of the protons are indicated on the structures shown below,

Figure 2-4. The sharing of the p-H$_2$ spin order for syn and anti-addition of propyne to propene. The numerical values indicate the fraction of the deposited p-H$_2$ spin order.
The theoretical enhancement factors at 300 K and 9.4 T and with 50% p-H$_2$, of the methine proton are $|\eta_{PE,cis}^{\text{theor}}| = 5209$ and $|\eta_{PE,trans}^{\text{theor}}| = 8126$. For an arbitrary syn-addition with a stereoselectivity $s$, the theoretical enhancement factor is,

$$|\eta_{PE}^{\text{theor}}(s)| = 5209 \cdot s + 8126 \cdot (1 - s)$$

(2-25)

**Pairwise Selectivity**

Pairwise selectivity of addition $\chi$ is defined as the ratio of number of added protons originating from the same dihydrogen molecule to the total number of added protons. It is calculated as the ratio of the experimental and theoretical enhancement factors,

$$\varphi = \frac{\eta_{\text{exp}}}{\eta_{\text{theor}}}$$

(2-26)
Parahydrogen Converters (50% and over 90% Enrichment)

A continuous stream of H₂ gas, enriched to approximately 50% p-H₂ is produced on demand by passing normal hydrogen (n-H₂, an approximate 1:3 mixture of p-H₂ and ortho-H₂, o-H₂) through a ¼ in. copper coil filled with iron (III) oxide (371254 ALDRICH) sandwiched by copper wool and submerged in liquid N₂ (77 K). With Swagelok and thick-wall PEEK tubing, the convertor can be pressurized up to 60 bar.

\[ X_{p-H_2} = (1 - 0.75 \times \frac{S_{p-H_2}}{S_{n-H_2}}) \times 100\% \]  

Equation (3-1)

According to Eq. (3-1), there is a 1/3 decrease in \(^1\text{H}\) NMR signal intensity of 50% p-H₂, compared to 25% p-H₂, as presented in Figure 3-1 A). The spectra collected at
continuous-flow rates of 100, 300, 500 and 700 mL/min, respectively, for 20 mins are presented in Figure 3-1B). For each flow rate, three spectra were collected – 0, 10 mins and 20 mins after turning on the gas flow. Because of the background signal from the probe, a background spectrum was collected and subtracted from all H₂ spectra. Sixteen transients were accumulated with a recycle delay of 5s. Apodization of 10 Hz was applied to all spectra. The fraction of p-H₂ was calculated according to Eq. (3-1).

As shown in Figure 2-1, ratio of para-ortho hydrogen at thermal equilibrium increases as temperature decreases. 99.7% enrichment of p-H₂ can be achieved at 21 K. Compared to 50% enrichment, there will be a three-fold gain in the PHIP enhancement factor (Eq. (2-24)). Construction of a converter that works at 21 K is underway. Figure 3-2 describes the composition of the converter. A home-built cryostat (part 9) is inserted into liquid He dewar which is at 4 K. The temperature of 21 K is stabilized by the balance of vacuum level in the cryostat and the heater (part 6) controlled by the Oxford intelligent temperature controller. The pressure relief valves (part 2) close to the gas inlet and outlet were set to a cracking pressure of 150 bar. The copper baffles (part 5) minimize the heat transfer by thermal radiation. The temperature range of a T-type thermocouple is 23 K to 623 K. At 30 K, 97% enrichment of p-H₂ can be achieved according to Eq. (2-3). The same catalysts used in the 50% p-H₂ converter were packed inside the heat exchanging copper helical coil (part 6), accelerating the conversion of ortho to parahydrogen. 99%-enriched p-H₂ will be collected and stored in an aluminum cylinder at room temperature. The spin relaxation time of p-H₂ inside the cylinder is around four months.
Figure 3-2. 99% p-H₂ converter operating at 21 K and up to 50 bar.

Figure 3-3. Schematic representation of the continuous-flow fixed-bed gas reactor.

As illustrated in Figure 3-3, the solid catalyst was packed into a 1/4 in. o.d. U-shaped glass tube mounted inside a ceramic heating element inside which the
temperature of the catalyst bed can be varied from \( \sim 25 \) to 400 °C. The reactor is mounted just above the bore opening of a 9.4 T Bruker Ultrashield actively shielded magnet, where the fringe field is 5 mT. The temperature of the reactor bed is monitored using a K-type thermocouple probe inserted directly into the bed. Nitrogen is used as buffer gas. The flow rates are controlled precisely by mass flow controller.

**Pressurized Liquid-phase Hydrogenation Reactor**

![Schematic representation of the pressurized gas/liquid/solid slurry reactor.](image)

Figure 3-4. Schematic representation of the pressurized gas/liquid/solid slurry reactor.

As illustrated in Figure 3-4, the design of the NMR tube slurry reactor facilitated hydrogenation at elevated pressures, which increases the concentration of dissolved p-H\(_2\) and elevates the boiling point of the solvent. By raising the reactor pressure from 1 bar to 5.7 bar, the boiling point of the solvent (e.g. D\(_2\)O) increases from 100 to 160 °C. Elutriation of the catalyst particles in the NMR tube reactor is achieved by bubbling p-H\(_2\) through the slurry using a 1/16 inch OD PEEK tube. Three pulse-programmed auxiliary TTL outputs on the Bruker Avance NMR spectrometer console were used to precisely control the actuation timing of the solenoid valves that controlled gas flow. A variable pressure relief valve was used to finely control the size of the bubbles. In the
PASADENA experiments, the temperature of the NMR tube was regulated to 80 °C using the variable temperature system of the Bruker spectrometer. In the ALTADENA experiments, the NMR tube was immersed in a hot oil bath at set temperatures for 15 minutes prior to reactions. After bubbling the p-H$_2$ gas, a back pressure was applied to stop the bubbling. The NMR tube was then manually inserted into the 400 MHz magnet as quickly as possible and a single free induction decay was acquired using a 90° pulse.
CHAPTER 4
PLATINUM-TIN INTERMETALLIC NANOPARTICLES

Background

Platinum is among the most versatile and active metals in heterogeneous catalysis. With applications to clean and renewable energy, Pt has been the subject of many fundamental studies, but its low selectivity, high cost, and susceptibility to poisoning drive the search for alternatives. Pt-Sn bimetallic catalysts offer key advantages for many types of reactions. In hydrogenation, Pt-Sn catalysts can provide higher selectivity while maintaining activity. Surface-science studies of adsorption of H on Pt-Sn surface alloys by Koel et al. in the 1990s revealed the importance of contiguous three-fold (111) Pt sites in dissociative H chemisorption. Elimination of three-fold Pt sites can be achieved upon incorporation of Sn. However, aggregation of Pt-Sn NPs during the high-temperature annealing treatment has hampered the elucidation of the role of these sites in hydrogenation catalysis. Recently, a facile approach to the synthesis of size-monodisperse nanoscale intermetallic compounds has been introduced. The well-defined Pt-Sn iNPs are encapsulated in a mesoporous silica (mSiO) shell which stabilizes them at high temperatures. We employed hetPHIP NMR to examine the effects of incorporating Sn on the pairwise selectivity (φ) of hydrogenation with these iNPs. Additionally, the Pt-Sn iNPs are shown to be a promising catalytic platform for hyperpolarization of gases and liquids that is suitable for in vivo magnetic resonance imaging.
Materials Synthesis and Characterizations

Synthesis of Pt@mSiO\textsubscript{2} NPs

The Pt@mSiO\textsubscript{2} nanoparticles were prepared according to the previously reported literature with a few modifications in the synthetic approach.\textsuperscript{54} Around 25 mL of a 10 mM K\textsubscript{2}PtCl\textsubscript{4} (Acros Organics, 46–47\% Pt) was added to 200 mL of a 125 mM aqueous solution of tetradecyltrimethylammonium bromide (TTAB, $\geq$ 99\%, Sigma-Aldrich). The above mixture was stirred for 10 minutes to obtain a cloudy white solution which was then moved to an oil bath maintained at 50 °C for 10 more minutes. When the cloudy solution turned clear, 25 mL of 300 mM sodium borohydride solution prepared in ice-cold water (Alfa Aesar, 98\%) was then added. After the solution was stirred for 20 h at 50 °C, the result was a dark brown colloidal solution of Pt nanoparticles. This was centrifuged at 3000 rpm four times for durations of 30 min, with the supernatant being collected while the residue was discarded. Finally, the supernatant was centrifuged at 14000 rpm for 15 min twice, collected, and redispersed in deionized water to obtain around 200 mL of the solution. About 1 mL of a 0.05 M sodium hydroxide solution was added to obtain a pH between 11 and 12. While stirring, 3 mL of a 10\% tetraethylorthosilicate (TEOS, Aldrich, reagent grade, 98\%) solution in methanol was added dropwise via syringe. After 24 h, the sample was centrifuged at 14000 rpm twice, and the coated particles (Pt@mSiO\textsubscript{2}) were redispersed in 200 mL of methanol. To this 10 mL of hydrochloric acid (36\% assay) was added and the solution was refluxed at 90 °C for 24 h. The platinum content in Pt@mSiO\textsubscript{2} was identified using ICP-MS.

Synthesis of Bimetallic Pt\textsubscript{3}Sn@mSiO\textsubscript{2} and PtSn@mSiO\textsubscript{2} NPs

The methanol-dispersed solution of Pt@mSiO\textsubscript{2} was centrifuged and redispersed in 75 mL of tetraethylene glycol (Alfa Aesar, 99\%) in a 250 mL two-neck flask. The
amount of Pt in a typical synthesis of Pt@mSiO$_2$ particles was 0.15 mmol.

Pt$_3$Sn@mSiO$_2$ was made ensuring a Pt:Sn molar ratio of 3:1, using SnCl$_2$·2H$_2$O (Alfa Aesar, 98%) as the source of Sn, and heating the solution at 280 °C for 2 hours to form the alloy. Subsequently, an equal volume of acetone was added and sonicated to obtain a homogeneous solution. This was then centrifuged and calcined at 500 °C for 4 hours to remove any remaining organic residues in the nanoparticles. The calcined sample was then reduced at 600 °C for 4 hours in a 10% H$_2$/Ar flow in a tube furnace to obtain intermetallic Pt$_3$Sn@mSiO$_2$. PtSn@mSiO$_2$ was prepared with a molar ratio of Pt:Sn = 1:1, heating the solution at 280 °C for 2 h. The resulting solution was diluted with an equal volume of acetone and centrifuged at 14000 rpm to obtain PtSn@mSiO$_2$ nanoparticles. This was then dried and calcined at 500 °C to remove any organic residues from the synthesis. The sample was then reduced in 10% H$_2$ in a tube furnace at 300 °C for 4 hours to obtain intermetallic PtSn@mSiO$_2$. Inductively coupled plasma mass spectrometry (ICP-MS) measurements were also carried out on the powdered samples to confirm their stoichiometry as per the synthesis.

**Synthesis of Pt/Silica Gel, Pt$_3$Sn/Silica Gel and PtSn/Silica Gel Supported on Silica Gel**

Colloidal Pt nanoparticles synthesized as detailed in the synthesis of Pt@mSiO$_2$, were supported on Silica gel instead of polymerizing tetraethylorthosilicate around the nanoparticles, via wetness impregnation. The respective intermetallics were synthesized using tetraethylene glycol and SnCl$_2$.2H$_2$O, following the exact synthetic methods used to prepare Pt$_3$Sn@mSiO$_2$ and PtSn@mSiO$_2$.

Transmission Electron Microscopy (TEM) measurements were carried out using a TECNAI G2 F20 at an acceleration voltage of 200 kV, as reported in earlier work.
Before the TEM measurements, all the samples were first calcined at 500 °C and then reduced at the appropriate temperature in a 50 mL/min 10% H₂ in Argon stream. All Pt and PtSn samples were reduced at 300 °C while Pt₃Sn samples were reduced at 600 °C. Powder X-ray diffraction (PXRD) patterns were collected at room temperature using an STOE Stadi P powder diffractometer equipped with an image plate and a Cu Kα1 radiation source (λ = 1.5406 Å). ICP-MS measurements were carried out using a Thermo Fisher Scientific X Series 2 spectrometer. Samples were dissolved in aqua regia to digest the metal nanoparticles, after which the least quantity of a 30% HF solution required to dissolve the mesoporous silica was added. The solution was heated to evaporate the resultant hexafluorosilicic acid, and the sample was diluted with 2% nitric acid before ICP-MS measurements were carried out.

CO chemisorption studies to obtain Pt dispersion were carried out as reported in previously published work, using a Micromeritics 3Flex surface characterization analyzer.⁵⁴ Around 150-200 mg of each sample was synthesized for the CO Chemisorption measurements. Prior to chemisorption measurements, all samples were calcined at 500 °C in air. Pt@mSiO₂ and PtSn@mSiO₂ were reduced at 300 °C, while Pt₃Sn@mSiO₂ was reduced at 600 °C, under 50 mL/min 10% H₂/He. CO chemisorption was conducted at 35 °C. Following an evacuation at 300 °C for 30 min using a turbomolecular pump, we obtained the first isotherm. The second isotherm was arrived at after evacuation at 35 °C for 1 h. The difference between the two isotherms was extrapolated to zero pressure to account for the irreversibly adsorbed CO. Using a ratio of CO/Pt = 1.5, Pt dispersion calculations were conducted.
X-ray photoelectron spectroscopy (XPS) measurements were performed using a PHI 5500 Multi-technique system (Physical Electronics, Chanhassen, MN) with a monochromatized Al Kα X-ray source (hv = 1486.6 eV). All data was energy calibrated with Si 2p at a binding energy of 103.5 eV. For both the Pt 4f and Sn 3d peaks, theoretical values for the peak area ratios in accordance with their spin-orbit splitting were used (0.75 for the Pt 4f5/2 to 4f7/2 peaks (Pt 4f5/2: Pt4f7/2 = 3:4) and 0.67 for the Sn 3d3/2 to 3d5/2 peaks (Sn 3d3/2: Sn3d5/2 = 2:3)) while fitting using CasaXPS. Peak widths (FWHM values), when comparing for the same element, were also made as similar as possible, keeping within acceptable limits of ±0.2 eV. All samples were measured immediately after reduction at 300 °C (Pt@mSiO2 and PtSn@mSiO2) or 600 °C (Pt3Sn@mSiO2) in 10% hydrogen. However, a short exposure to air is unavoidable before we load these samples into XPS chamber.

Inductively coupled plasma mass spectrometry (ICP – MS Perkin-Elmer Corp. NexION 300X) analysis was performed on the supernatant obtained from the aqueous slurry (centrifuged at 14,000 rpm for 10 minutes followed by decantation, twice). 1mL supernatant was diluted to 3 mL with a final concentration of 10% HCl and 1% HNO3. Multi-element calibration standard 4 (Lot# CL10-138YPY1) was used to establish the calibration curve and QA/QC protocols.

Pt3Sn@mSiO2 and PtSn@mSiO2 iNPs were prepared by an encapsulation-mediated synthesis. Size increases upon converting the Pt@mSiO2 (~14 nm metal core) to Pt3Sn@mSiO2 (~17 nm metal core) or PtSn@mSiO2 (~21 nm metal core) NPs (Figure 4-1) were observed under TEM, indicating incorporation of Sn into the Pt nanoparticles. Pt dispersion, as measured by CO adsorption, agrees with the formation
of the alloys and indicates an increase in size going from monometallic Pt to the Pt-Sn iNPs (Table 4-1). The metal loading of Pt and Sn were measured by ICP-MS (Table 4-1), confirming that the desired stoichiometry for the Pt-Sn iNPs was obtained. Reduction in 10% H₂ at 600 °C after synthesis affords the Pt₃Sn intermetallic compound (Pt:Sn=3:1). A lower temperature treatment of 300 °C afforded the PtSn (Pt:Sn=1:1) intermetallic compound. PXRD patterns in Figure 4-1 confirm the formation of the Pt₃Sn and PtSn intermetallic phases, in agreement with the simulated patterns and the high-resolution TEM micrographs (Figure 4-2). The pore size of the mesoporous silica (mSiO₂) shell has a diameter of 2.7 nm.⁴⁶ Both surface Pt and Sn in these samples are mainly in their metallic state (Figure 4-3, Figure 4-4 and Figure 4-5) even though the freshly reduced samples were exposed to air before loading into the XPS chamber.

![Figure 4-1. TEM images, structural models and PXRD patterns for A) Pt@mSiO₂, B) Pt₃Sn@mSiO₂, and C) PtSn@mSiO₂. Metal core diameters (in nm), determined from TEM, are 14.3 ± 0.8 (Pt), 16.6 ± 0.9 (Pt₃Sn), and 20.6 ± 0.9 (PtSn). Sn atoms are shown in orange. The blue triangle indicates the three-fold Pt sites discussed in the text. Materials synthesized by Mr. Raghu Maligal-Ganesh from Iowa State University. Reproduced with permission from ref. ⁵⁵ © John Wiley & Sons, Ltd., 2017.](image-url)
Table 4-1. Metal Loading, Particle Size and Pt Dispersion of the Mesoporous Silica-Encapsulated NPs.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pt Loading$^a$</th>
<th>Sn Loading</th>
<th>Core Size$^b$ (nm)</th>
<th>Pt Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt@mSiO$_2$</td>
<td>44.5%</td>
<td>0%</td>
<td>14.3 ± 0.8</td>
<td>6.5%</td>
</tr>
<tr>
<td>Pt$_3$Sn@mSiO$_2$</td>
<td>52.0%</td>
<td>9.0%</td>
<td>16.6 ± 0.9</td>
<td>2.8%</td>
</tr>
<tr>
<td>PtSn@mSiO$_2$</td>
<td>36.6%</td>
<td>22.4%</td>
<td>20.6 ± 0.9</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

$^a$Metal loadings were measured based on weight percentage; $^b$diameter of the metal core.

Figure 4-2. HRTEM images of A) Pt@mSiO$_2$ B) Pt$_3$Sn@mSiO$_2$ C) PtSn@mSiO$_2$. Lattice spacings are also indicated and correspond well with their respective planes as observed in standard Powder XRD data for these nanoparticles. Note that the observed lattice spacings in the HRTEM are orientation-dependent. The lattice spacing between (110) facets of PtSn@mSiO$_2$ was reported previously.$^{54}$

Figure 4-3. XPS spectrum of Pt in Pt@mSiO$_2$. Binding energy for surface Pt in Pt@mSiO$_2$ indicates that Pt was predominantly metallic Pt. The ionic component at 72.7 eV (10% of total peak area) could be due to surface oxides (PtO$_x$ species) generated upon exposure to air before we loaded the sample into XPS chamber.
Figure 4-4. XPS spectra of Pt in A) Pt₃Sn@mSiO₂ and B) PtSn@mSiO₂. Surface Pt in both of the two intermetallic samples are mainly in Pt(0). For Pt₃Sn@mSiO₂, we need to add the PtOₓ component to fit the XPS spectrum, and the PtOₓ only accounts for 8% of total peak area. The FWHM of the peaks is 2.2 eV for both Pt₃Sn and PtSn.

Figure 4-5. XPS spectra of Sn in A) Pt₃Sn@mSiO₂ and B) PtSn@mSiO₂. In both Pt₃Sn@mSiO₂ and PtSn@mSiO₂ Sn is predominantly metallic. However, SnOₓ species are also present (9% for Pt₃Sn and 15% for PtSn). The FWHM of the peaks is 2.2 eV for both Pt₃Sn and PtSn. The surface Pt at % is 71 and 48% for Pt₃Sn@mSiO₂ and PtSn@mSiO₂, which are very close to the theoretical values.

**PHIP NMR Experiments**

All catalysts were reduced in 10% H₂ in N₂ at a flow rate of 100 mL/min at 300 °C for 2h prior to the NMR experiments. Hydrogenations were performed using para-enriched H₂ gas (p-H₂, 50% parahydrogen) or normal H₂ gas (n-H₂, 25% parahydrogen). Elutriation of the catalyst particles in the NMR tube reactor is achieved by bubbling p-H₂ through the slurry using a 1/16 inch OD PEEK tube.
For the gas-phase reaction, hydrogenation reactions were performed using a reactant mixture containing H₂ (50% para-enriched), PE, and N₂ prepared with mass flow rates of 120, 210, and 70 mL/min, respectively, at a total pressure of 1 bar. The 400 MHz proton spectra were acquired in continuous-flow mode by signal averaging 16 transients with a recycle delay of 2 s. Temperature dependent experiments start at 300 °C, followed by 200 °C and 100 °C sequentially. For each catalyst, the experiments were repeated once immediately after the first run of temperature-dependent experiments under identical conditions. The pure PHIP-NMR spectra presented in all related figures were obtained by subtracting spectra acquired with n-H₂ (25% parahydrogen) from the spectra with p-H₂ (50% parahydrogen). The broad residual peak due to the o-H₂ content of the unreacted H₂ gas, which is different in p-H₂ and n-H₂, was removed from the difference spectrum by incorporation into the cubic spline baseline correction.

Using the NMR tube slurry reactor, ALTADENA mode PHIP NMR spectra of 2-hydroxyethyl propionate (HEP) (Sigma-Aldrich) in D₂O (1% in volume) were acquired following hydrogenation reactions at 5.0 mT. The NMR tube was loaded with 50 mg of insoluble catalyst powder and the dissolved substrates. The solution was deoxygenated by bubbling N₂ at a flow rate of 50 mL/min for 5 minutes. The head-space of the NMR tube was purged with p-H₂ gas for 2 minutes at a flow rate of 300 mL/min. The NMR tube was then pressurized to 5.7 bar with p-H₂. The NMR tube slurry reactor was immersed in a hot oil bath at set temperatures for 15 minutes prior to reactions. After bubbling the p-H₂ gas through the slurry for 20 s at a flow rate of 150 mL/min, a back pressure was applied to stop the bubbling. The NMR tube was then manually inserted into the 400 MHz magnet, as quickly as possible and a single free induction decay was
acquired using a 90° pulse. The slurry-type reactor is suitable for non-volatile, higher mass substrates, and the design facilitated hydrogenation studies at elevated pressures, which increases the concentration of dissolved p-H₂, increases the boiling point of the solvent, and allows reactions to be run at higher temperatures. To produce the hyperpolarized singlet state, Dimethyl acetylene dicarboxylate (Sigma-Aldrich, D138401) was dissolved in methanol-d₄ (Cambridge Isotope, DLM-24-10) at a volume ratio of 1:100 in a glove bag filled with N₂. The spontaneous precipitation of the Pt₃Sn@mSiO₂ catalysts does not require extra steps of catalyst and product separation. After NMR data acquisition, the product supernatant was withdrawn from the NMR tube by an NMR pipette and the same batch of catalysts were kept at the bottom and reused for next experiment with fresh reactant solution recharged.

To determine the pairwise selectivity ($\phi$) and total conversion $\chi^{PE}$ of PE to PA thermally polarized NMR spectra of the reaction products were collected by stopping the flow and signal averaging of either 16 transients (for Pt@mSiO₂ and Pt₃Sn@mSiO₂) or 32 transients (for PtSn@mSiO₂) using a recycle delay of 5 s, immediately following the acquisition of PHIP NMR spectra.

**Calculations of Conversion**

The calculation of the conversion, reported as $\chi$, depends on whether PE or H₂ is the limiting reagent:

$\chi^{PE} \rightarrow \chi$ if PE is limiting.

$\chi^{H₂} \rightarrow \chi$ if H₂ is limiting.

The uncertainties take the errors from baseline correction and peak integration into account. Several different methods of baseline correction and peak integration were
utilized, and errors were propagated. Reported errors represent the 90% confidence intervals. At low χ, a correction for the presence of 0.12 ± 0.02 % PA impurity in the stock PE gas cylinder (calculated from the NMR spectrum of a sealed PE gas sampled obtained directly from the gas cylinder) was applied to the measured PA peak integrals.

The conversion χ\textsuperscript{PE} were calculated by solving Eq.(4-1) and Eq.(4-2),

\[
\frac{S_{PE,CH_3}^{therm} \, \dagger}{3} \times X_{impurity} \times 6 + \frac{S_{PE,CH_3}^{therm} \, \dagger}{3} \times \chi^{PE} \times 6 = S_{PA,CH_3}^{therm} \tag{4-1}
\]

\[
S_{PE,CH_3}^{therm} \, \dagger - S_{PE,CH_3}^{therm} \, \dagger \times \chi^{PE} = S_{PE,CH_3}^{therm} \tag{4-2}
\]

The percent conversion of PE to PA is obtained,

\[
\chi^{PE} = \frac{S_{PA,CH_3}^{therm}}{S_{PA,CH_3}^{therm} / 2 + S_{PE,CH_3}^{therm}} \times 100\% \tag{4-3}
\]

When H\textsubscript{2} is the limiting reagent, e.g. at the flow rate of PE/H\textsubscript{2}/N\textsubscript{2}=210/120/70 mL/min, conversion of H\textsubscript{2} was calculated from Eq. (4-4)

\[
\chi^{H_2} = \chi^{PE} \times \frac{210}{120} \tag{4-4}
\]

where

\[
\chi^{PE} = \text{conversion of PE to PA, calculated.}
\]

\[
\chi^{H_2} = \text{conversion of H}_2 \text{ to PA, calculated.}
\]

\[
X_{impurity} = \text{impurity PA (mole fraction) in the PE precursor, 0.12% measured.}
\]

\[
S_{PA,CH_3}^{therm} = \text{thermally polarized NMR signal integral of the PA methyl group including impurity, measured.}
\]

\[
S_{PE,CH_3}^{therm} \, \dagger = \text{thermally polarized NMR signal integral of the PE methyl group before reaction, calculated.}
\]
\[ S_{PE, CH_3}^{therm} = \text{thermally polarized NMR signal integral of the PE methyl group after reaction, measured.} \]

The experimental signal enhancement factors were calculated according to Eq. (2-16) after deduction of PA impurity. The pairwise selectivity was calculated according to Eq. (2-26).

The conversion and selectivity of the dimethyl acetylene dicarboxylate (DMAC) hydrogenation reaction was calculated based on the signal integral of -CH\(_3\) (3.9 ppm) groups in DMAC, -CH (6.4 ppm) groups in dimethyl maleate (DMM), -CH (6.9 ppm) groups in dimethyl fumarate (DMF) and -CH\(_2\) (2.7 ppm) groups in dimethyl succinate (DMS) in the thermally polarized spectra. Because of the signal overlap of -CH\(_3\) (3.9 ppm) groups in DMAC and DMM, the peaks were deconvoluted in MestReNova before integration.

Total conversion (\(\chi_{DMAC}\)) of DMAC is calculated as,

\[
\chi_{DMAC} = \frac{I_{DMM-CH} + I_{DMF-CH} + I_{DMS-CH_2}/2}{I_{DMAC-CH_3}/3 + I_{DMM-CH} + I_{DMF-CH} + I_{DMS-CH_2}/2} \quad (4-5)
\]

Selectivity of DMM (\(\varphi_{DMM}\)), DMF (\(\varphi_{DMF}\)) and DMS (\(\varphi_{DMS}\)) is calculated as

\[
\varphi_{DMM} = \frac{I_{DMM-CH}}{I_{DMM-CH} + I_{DMF-CH} + I_{DMS-CH_2}/2} \quad (4-6)
\]

\[
\varphi_{DMF} = \frac{I_{DMF-CH}}{I_{DMM-CH} + I_{DMF-CH} + I_{DMS-CH_2}/2} \quad (4-7)
\]

\[
\varphi_{DMS} = \frac{I_{DMS-CH_2}/2}{I_{DMM-CH} + I_{DMF-CH} + I_{DMS-CH_2}/2} \quad (4-8)
\]

Where \(I\) denotes the NMR signal integral.
Detection of Singlet State

Level Anti-crossing State Mixing

A) *cis*, maleate

B) *trans*, fumarate

Figure 4-6. The *J*-coupling networks of A) DMM and B) DMF. $J_{23}=11.6\text{ Hz}$, $J_{24}-J_{34}=0.4\text{ Hz}$, $J_{67}=18.0\text{ Hz}$, $J_{78}-J_{68}=0.4\text{ Hz}$.

It has been demonstrated that in a AA'XX' system (two chemically equivalent but magnetically inequivalent pairs), there is level anti-crossing state mixing as a function of magnetic field strength and *J*-couplings among the protons. Figure 4-6 presents the *J*-coupling networks of DMM and DMF. In the singlet-triplet basis for the two spin pairs in DMM, states $|T_{2,3}^{2,3}S_{4,5}^{4,5}\rangle$ and $|S_{2,3}^{2,3}T_{4,5}^{4,5}\rangle$, $|T_{2,3}^{2,3}T_{4,5}^{4,5}\rangle$ and $|S_{2,3}^{2,3}S_{4,5}^{4,5}\rangle$ are mixed at the level anti-crossing point, where the chemical shift difference between the two spin pairs is equal to the *J*-coupling between proton 2 and 3 ($J_{23}=11.6\text{ Hz}$),

$$\Delta \nu_{2,3-4,5} = \Delta \nu_{2,3} - \Delta \nu_{4,5} = J_{23} \quad (4-9)$$

Thus, the magnetic field strength where the level anti-crossing happens for DMM is,

$$B_{0}^{\text{maleate}} = 0.10T \quad (4-10)$$

For DMF, $J_{67}=18.0\text{ Hz}$, level anti-crossing happens at

$$B_{0}^{\text{fumarate}} = 0.13T \quad (4-11)$$
As described in Figure 4-7A, after hydrogenation at earth magnetic field (~70 μT), the NMR tube was immersed to an ice bath for a waiting time $t_w$ (for each $t_w$, the same catalyst and a fresh reactant solution was used). It was then manually inserted, descended to the stray magnetic field at 0.1 T (measured by a Gaussmeter) and stay at 0.1 T for 20 s in a 400 MHz magnet. Then it is manually descended to the detection region at 9.4 T as quickly as possible, followed by a 90° RF pulse and NMR data acquisition. After 1 min, thermally polarized spectra were acquired by another 90° RF pulse.

Figure 4-7. Schemes of the hydrogenation reactions, sample transfer and readout of singlet state at the designated magnetic field and time by A) level anti-crossing effect and B) SLIC pulse sequence.
Multiple-conversion Spin Locking Induced Crossing (SLIC) RF Pulse Sequence

SLIC is a simple and effective spin lock pulse which composes of a low power RF pulse that matches the stronger $J$-coupling between the proton pairs in a AA'XX' system to convert the singlet into observable magnetization.\textsuperscript{57,58} In dimethyl maleate, the maximum conversion happens when the RF pulse strength $\nu_1$ is equal to $J_{23}$, 

$$\nu_1 = J_{23} \quad (4-12)$$

and pulse duration

$$\tau_{SL} = \frac{\sqrt{2}}{2(J_{24} - J_{34})} \quad (4-13)$$

Thus, the optimized RF power $\nu_1 = 11.6 \text{Hz}$ and pulse duration $\tau_{SL} = 1.77 \text{s}.$

To measure the singlet lifetime $T_s$, a multiple-conversion SLIC pulse sequence was adapted, with a slight modification.\textsuperscript{57,59} A $90^\circ$ pulse with the same phase to the lock pulse was applied 5ms before the lock pulse to saturate the thermally polarized signal each time. The same phase ensures the minimum effect of the spin lock on the thermally polarized signal. As described in Figure 4-7B, consecutive SLIC pulse was applied with a time interval $\Delta t$ between the repetitions for $n$ times. The signal intensity from the $n$-th conversion $I_n$ was derived to be,\textsuperscript{59}

$$I_n = I_0(1 - \xi)^n \exp\left(-\frac{n\Delta t}{T_s}\right) \quad (4-14)$$

$I_0$ is the signal intensity acquired from the first SLIC pulse. $\xi$ is the efficiency of the singlet-to-magnetization conversion of a single SLIC pulse. $T_s$ is the spin relaxation time of the singlet state. Rearrange equation (4-14), normalize the signal intensity obtained from $n$-th SLIC pulse with respect to that obtained from the 1$^{st}$ SLIC pulse,
Fit the normalized signal intensity to an exponential function with a variable \( n \) according to equation (4-15), a characteristic exponential decay rate \( \lambda \) is obtained,

\[
\frac{I_n}{I_0} = \exp(n\ln(1 - \xi) - \frac{n\Delta t}{T_s}) \tag{4-15}
\]

\[
\frac{I_n}{I_0} = \exp(-\lambda n) \tag{4-16}
\]

and \( \lambda \) is defined as,

\[
\lambda = -\ln(1 - \xi) + \frac{1}{T_s}\Delta t \tag{4-17}
\]

Equation (4-17) indicates that linear fitting of \( \lambda \) to the variable \( \Delta t \) yields \( T_s \) (from the slope) and \( \xi \) (from the intercept with y axis).

Figure 4-7B describes the experiments that were performed using multiple-conversion SLIC pulse sequence. After hydrogenation at earth magnetic field (~70 μT), the NMR tube was manually inserted into the 400 MHz magnet as quickly as possible, followed immediately by applying a 90° pulse to eliminate any hyperpolarized signal arising from passing through the level anti-crossing point at 0.1T. After a waiting time of 60s, multiple-conversion SLIC pulse sequence was initiated with a time interval \( \Delta t \). Each spectrum after the SLIC pulse sequence was stored in a pseudo 2D experiments. The process described in Figure 4-7B was repeated with \( \Delta t s \) of 30, 40, 50, 60, 80 s using the same catalyst and fresh reactant solution. Cubic spline baseline correction was performed to eliminate the residue of thermally polarized signal before the integration of the vinylene peaks at 6.4 ppm. A line broadening of 3 Hz was applied to all spectra.
Results and Discussion

Hyperpolarization in Gaseous Phase

The $^1$H NMR spectra produced by reaction of p-H$_2$ with propene (PE) over the mSiO$_2$-encapsulated catalysts in the fixed bed reactor are presented in the lower panels of Figure 4-8 and Figure 4-9 for bed temperatures of 100, 200, and 300 °C. Propane (PA) exhibits the ALTADENA net alignment signal pattern (–CH$_3$ multiplet in emission phase). The thermally polarized spectra acquired at 300 °C are presented in the upper panels of Figure 4-8 and Figure 4-10. The intensities of the PA peaks (labelled “a” and “b”) in the thermally polarized spectra are proportional to total PE → PA conversion (random + pairwise), denoted $\chi$. Pairwise selectivity $\varphi$ is calculated from the ratio of the experimental and theoretical signal enhancements, $\varphi = \eta^{\text{exp}} / \eta^{\text{theory}}$. Figure 4-11 and Table 4-2, Table 4-3 and Table 4-4 report $\chi$, $\varphi$, and $\eta^{\text{exp}}$ obtained using 10 mg of Pt@mSiO$_2$, Pt$_3$Sn@mSiO$_2$ and PtSn@mSiO$_2$ at 100, 200 and 300 °C. Good reproducibility of the experimental data was obtained.
Figure 4-8. Thermally polarized (top) and hyperpolarized (bottom) $^1$H NMR spectra of reactor effluent obtained using 10 mg of A) Pt@mSiO$_2$, B) Pt$_3$Sn@mSiO$_2$ and C) PtSn@mSiO$_2$ at 300 °C. The reactant flow rates were 120 mL/min H$_2$; 210 mL/min PE; 70 mL/min N$_2$. All spectra are displayed on the same vertical scale.

Figure 4-9. 400 MHz ALTADENA $^1$H NMR spectra of products obtained using 10 mg A) Pt@mSiO$_2$ B) Pt$_3$Sn@mSiO$_2$ and C) PtSn@mSiO$_2$ at 100 °C, 200 °C and 300 °C. 16 transients were accumulated for all spectra. Flow rate: 120 mL/min H$_2$; 210 mL/min PE; 70 mL/min N$_2$. The vertical scale is the same for all spectra.
At 300 °C, monometallic Pt@mSiO₂ catalyst produced only a very weak ALTADENA NMR signal. In contrast, the Pt₃Sn@mSiO₂ and PtSn@mSiO₂ catalysts both produced strong ALTADENA peaks with similar intensities. Despite the drastically lower activity exhibited by PtSn@mSiO₂ (compare the “a” peaks in the spectra of the upper panels of Figure 4-8 and Figure 4-10), this catalyst still gave the strongest ALTADENA signals. Thus, PtSn@mSiO₂ delivered the highest $\eta^{\text{exp}}$ and $\phi$. A remarkable 3000-fold increase in signal enhancement relative to the monometallic Pt@mSiO₂ NPs ($\eta^{\text{exp}} = 0.20 \pm 0.07$ and $\phi = 0.0020 \pm 0.0007\%$) was observed (see Table 4-2). Meanwhile, $\lambda$ decreases precipitously upon incorporation of Sn (Figure
4-11 and Table 4-4), following the order Pt@mSiO$_2$ (19.5%) > Pt$_3$Sn@mSiO$_2$ (17%) ≫ PtSn@mSiO$_2$ (0.3%) at 300 °C.

Figure 4-11. A, B) Temperature dependence of pairwise selectivity, $\phi$, ALTADENA signal enhancement factor, $\eta_{\text{exp}}$, and PE to PA conversion, $\chi$, for Pt@mSiO$_2$, Pt$_3$Sn@mSiO$_2$ and PtSn@mSiO$_2$ (10mg, synthetic batch 1) at 100, 200 and 300 °C (blue, red, green bars, respectively). C) Linear dependence of conversion and pairwise selectivity on H$_2$ partial pressure for two substrate pressures (50mg PtSn@mSiO$_2$, batch 2). D) Linear dependence of pairwise selectivity, enhancement factor, and conversion on PtSn@mSiO$_2$ catalyst mass (batch 2).
Figure 4-12. A) ALTADENA and B) thermally polarized 400 MHz 1H NMR spectra of products obtained using 10, 30, 50 mg PtSn@mSiO$_2$ (a different batch from the one used for the temperature-dependent experiments) at 300 °C. 16 transients were accumulated for all spectra. Flow rate: 120 mL/min H$_2$; 210 mL/min PE; 70 mL/min N$_2$. The vertical scale is the same for all spectra.

Table 4-2. ALTADENA NMR signal Enhancement Factor ($
\eta^{\text{exp}}$
) of Mesoporous Silica-Encapsulated Catalysts at a Flow Rate of PE/H$_2$/N$_2=210/120/70$ mL/min.

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Pt@mSiO$_2$</th>
<th>Pt$_3$Sn@mSiO$_2$</th>
<th>PtSn@mSiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1$^{\text{st}}$ run</td>
<td>2$^{\text{nd}}$ run</td>
<td>1$^{\text{st}}$ run</td>
</tr>
<tr>
<td>100</td>
<td>0.4 ± 0.04</td>
<td>0.5 ± 0.04</td>
<td>76.3 ± 7.17</td>
</tr>
<tr>
<td>200</td>
<td>0.4 ± 0.1</td>
<td>0.5 ± 0.09</td>
<td>67.1 ± 4.82</td>
</tr>
<tr>
<td>300</td>
<td>0.2 ± 0.07</td>
<td>0.3 ± 0.06</td>
<td>13.2 ± 0.51</td>
</tr>
</tbody>
</table>

Table 4-3. Pairwise Selectivity ($\phi$) of Mesoporous Silica-Encapsulated Catalysts at a Flow Rate of PE/H$_2$/N$_2=210/120/70$ mL/min.

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Pt@mSiO$_2$</th>
<th>Pt$_3$Sn@mSiO$_2$</th>
<th>PtSn@mSiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1$^{\text{st}}$ run</td>
<td>2$^{\text{nd}}$ run</td>
<td>1$^{\text{st}}$ run</td>
</tr>
<tr>
<td>100</td>
<td>0.003 ±</td>
<td>0.005 ±</td>
<td>0.733 ±</td>
</tr>
<tr>
<td></td>
<td>0.0002%</td>
<td>0.0004%</td>
<td>0.0688%</td>
</tr>
<tr>
<td>200</td>
<td>0.003 ±</td>
<td>0.005 ±</td>
<td>0.644 ±</td>
</tr>
<tr>
<td></td>
<td>0.0005%</td>
<td>0.0009%</td>
<td>0.0463%</td>
</tr>
<tr>
<td>300</td>
<td>0.002 ±</td>
<td>0.003 ±</td>
<td>0.127 ±</td>
</tr>
<tr>
<td></td>
<td>0.0007%</td>
<td>0.0006%</td>
<td>0.0049%</td>
</tr>
</tbody>
</table>
Figure 4-13. A) ALTADENA and B) thermally polarized 400 MHz $^1$H NMR spectra of products obtained at increasing $H_2$ partial pressure while keeping PE partial pressure at 0.25 bar, using 50 mg PtSn@mSiO$_2$ (synthetic batch 2) at 300 °C. 16 transients were accumulated for all spectra. The reactor pressure was kept at 1 bar with $N_2$ gas as the carrier gas. The total flow rate is 400 mL/min. The vertical scale is the same for all spectra.

Table 4-4. Percent Conversion of $H_2$ and PE at a Flow Rate of PE/H$_2$/N$_2_=$210/120/70 mL/min Using Mesoporous Silica-Encapsulated Catalysts

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Pt@mSiO$_2$</th>
<th>Pt$_3$Sn@mSiO$_2$</th>
<th>PtSn@mSiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st run</td>
<td>2nd run</td>
<td>1st run</td>
</tr>
<tr>
<td>100</td>
<td>28.7 ± 2.07%</td>
<td>24.2 ± 1.21%</td>
<td>0.5 ± 0.07%</td>
</tr>
<tr>
<td>200</td>
<td>24.5 ± 0.53%</td>
<td>20.1 ± 1.46%</td>
<td>2.4 ± 0.06%</td>
</tr>
<tr>
<td>300</td>
<td>19.5 ± 1.27%</td>
<td>15.5 ± 1.45%</td>
<td>17.0 ± 0.43%</td>
</tr>
</tbody>
</table>

As seen in Figure 4-11B, conversion over Pt@mSiO$_2$ slightly decreased with increased temperature. This could be due to coke formation on the pure Pt NPs where a high activity of hydrogenation may induce local heating. Koel et al. reported a 35% PE decomposition on Pt(111) during the TPD experiment, ~5-7% decomposition on Pt$_3$Sn, and no decomposition on Pt$_2$Sn as substrate temperature increased. It was proposed
that PE decomposition is also catalyzed on contiguous pure-Pt threefold hollow sites.\textsuperscript{48} A slight reduction in $\chi$ was observed over Pt@mSiO$_2$ and Pt$_3$Sn@mSiO$_2$ in the second run of the reaction, possibly due to the blocking of some active sites by carbonaceous deposits.

The preceding results were obtained using only 10 mg of PtSn@mSiO$_2$ iNPs and 300 mbar H$_2$. The low conversion achieved for these conditions, attributed to the weak physisorption of H$_2$ for these iNPs, would be inadequate for most applications. Therefore, additional experiments were performed to investigate the scaling of $\varphi$ and $\chi$ with catalyst mass and H$_2$ partial pressure. Figure 4-11C, Figure 4-12 and Figure 4-13 show a linear scaling of $\chi$ with $P_{H_2}$ with little change in $\varphi$. Figure 4-11D and Figure 4-12 show that $\chi$ also scales linearly with catalyst mass from 10 to 50 mg without significant loss of pairwise selectivity. In these experiments, which were performed on a separate synthetic batch of PtSn@mSiO$_2$, enhancement factors $\eta^{\text{exp}}>10^3$ were observed, corresponding to $\varphi > 10\%$, setting a world record for any heterogeneous NP catalyst. While our setup did not permit these studies to be extended to higher pressure and mass, the results clearly demonstrate that higher conversions can likely be achieved. We hypothesize that the slight differences in $\varphi$ and $\chi$ of the two catalyst batches are due to variations in uniformity of Pt and Sn surface atomic distributions that exist despite having the same 1:1 atomic ratio in the bulk. For the reactions run at 300 °C with 10 mg, the second batch exhibited a higher $\varphi$ (10.4% vs 7.5%) and a lower $\chi$ (0.2% vs 0.3%) than the first batch, consistent with anticorrelation of $\varphi$ and $\chi$, and lower surface Pt:Sn ratio for the second synthetic batch.
The dramatic increase in $\varphi$, accompanied by a decrease in $\chi$, is consistent with fewer threefold Pt sites on the ordered PtSn(110) surface compared to Pt(111) and Pt$_3$Sn(111). A Pt(111) surface consists of contiguous pure-Pt threefold sites, while Pt$_3$Sn(111) bears isolated pure-Pt threefold sites, and Pt$_2$Sn(111) is devoid of the threefold sites. Note that the mole fraction of Sn in our PtSn@mSiO$_2$ catalyst (Pt:Sn=1:1) is even higher than in the Sn/Pt$_2$ (111) surface alloy study. The surface alloy studies on Pt, Pt$_3$Sn, and Pt$_2$Sn single crystal surfaces have shown the threefold Pt hollow sites to be essential for dissociative adsorption of H$_2$.\textsuperscript{47-50} Chemisorption of H$_2$ on the Sn/Pt$_2$(111) surface alloys at room temperature was found to be limited to only 2% of the saturation coverage of hydrogen on clean Pt(111). In contrast, atomic hydrogen readily adsorbs on the alloy surfaces at temperatures down to 150 K,\textsuperscript{47} indicating that H$_2$ chemisorption is inhibited by kinetic rather than thermodynamic factors (high H$_2$ dissociation barrier).\textsuperscript{6,7}

Due to the facile dissociative adsorption of H$_2$ and high rate of stepwise addition of H ad-atoms to the alkene in the Horiuti-Polanyi mechanism, conversion by direct hydrogenation is extremely low for monometallic Pt NPs. The non-linear dependence of $\varphi$ on Sn implicates the Pt threefold hollow sites in the catalysis by random addition. With increasing Sn fraction, $\varphi$ also increases because of decreased H$_2$ chemisorption along with a possible increase in direct hydrogenation. There could also be a corresponding increase in the number of sites that bind molecular H$_2$ and serve as active sites for direct hydrogenation.
Figure 4-14. Thermally polarized (top) and PHIP (bottom) 400 MHz $^1$H NMR spectra of reactor effluent obtained using A) 10 mg 1% Pt/Silica Gel, B) 106 mg 4.2% Pt/Silica Gel, C) 113 mg Pt$_3$Sn/Silica Gel and D) 87 mg PtSn/Silica Gel at 300 °C. 16 transients were accumulated for all spectra. Line broadening of 3Hz was applied. The vertical scale is the same for all spectra.

Figure 4-15. 400 MHz ALTADENA $^1$H NMR spectra of products obtained using 10 mg A) 10 mg 1% Pt/Silica Gel, B) 106 mg 4.2% Pt/Silica Gel, C) 113 mg Pt$_3$Sn/Silica Gel and D) 87 mg PtSn/Silica Gel at 100 °C, 200 °C and 300 °C. 16 transients were accumulated for all spectra. Flow rate: 120 mL/min H$_2$; 210 mL/min PE; 70 mL/min N$_2$. The vertical scale is the same for all spectra.
Figure 4-16. Thermally polarized 400 MHz $^1$H NMR spectra of reactor effluent obtained using A) 10 mg 1% Pt/Silica Gel, B) 106 mg 4.2% Pt/Silica Gel, C) 113 mg Pt$_5$Sn/Silica Gel and D) 87 mg PtSn/Silica Gel at 100 °C, 200 °C and 300 °C. 16 transients were accumulated for all spectra. Reactant flow rates: 120 mL/min H$_2$; 210 mL/min PE; 70 mL/min N$_2$. Line broadening of 3Hz was applied. The vertical scale is the same for all spectra.

Table 4-5. PHIP Enhancement Factor (EF) of Silica Gel Supported Catalyst at a Flow Rate of PE/H$_2$/N$_2$=210/120/70 mL/min

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>1% Pt</th>
<th>4.2% Pt</th>
<th>Pt$_5$Sn</th>
<th>PtSn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st run</td>
<td>2nd run</td>
<td>1st run</td>
<td>2nd run</td>
</tr>
<tr>
<td>100</td>
<td>5.0 ± 1.14</td>
<td>4.0 ± 0.96</td>
<td>3.4 ± 0.45</td>
<td>3.2 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>70.5 ± 6.12</td>
<td>76.6 ± 3.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>12.6 ± 2.04</td>
<td>13.9 ± 1.86</td>
<td>4.6 ± 0.22</td>
<td>4.6 ± 0.61</td>
</tr>
<tr>
<td></td>
<td>265.8 ± 23.41</td>
<td>243.3 ± 42.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>23.4 ± 1.77</td>
<td>21.1 ± 3.94</td>
<td>6.3 ± 0.12</td>
<td>6.6 ± 0.45</td>
</tr>
<tr>
<td></td>
<td>292.2 ± 26.34</td>
<td>301.0 ± 26.83</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4-6. Pairwise Selectivity (PS) of Silica Gel Supported Catalyst at a Flow Rate of PE/H\textsubscript{2}/N\textsubscript{2}=210/120/70 mL/min

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>1% Pt</th>
<th>4.2% Pt</th>
<th>Pt\textsubscript{3}Sn</th>
<th>PtSn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1\textsuperscript{st} run</td>
<td>2\textsuperscript{nd} run</td>
<td>1\textsuperscript{st} run</td>
<td>2\textsuperscript{nd} run</td>
</tr>
<tr>
<td>100</td>
<td>0.048±0.0109%</td>
<td>0.038±0.0093%</td>
<td>0.032±0.0043%</td>
<td>0.031±0.0026%</td>
</tr>
<tr>
<td>200</td>
<td>0.121±0.0196%</td>
<td>0.133±0.0178%</td>
<td>0.044±0.0021%</td>
<td>0.044±0.0059%</td>
</tr>
<tr>
<td>300</td>
<td>0.224±0.0170%</td>
<td>0.202±0.038%</td>
<td>0.061±0.0011%</td>
<td>0.063±0.0043%</td>
</tr>
</tbody>
</table>

Table 4-7. Percent Conversion of H\textsubscript{2} and PE at a Flow Rate of PE/H\textsubscript{2}/N\textsubscript{2}=210/120/70 mL/min Using Silica Gel Supported Catalysts

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>1% Pt</th>
<th>4.2% Pt</th>
<th>Pt\textsubscript{3}Sn</th>
<th>PtSn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1\textsuperscript{st} run</td>
<td>2\textsuperscript{nd} run</td>
<td>1\textsuperscript{st} run</td>
<td>2\textsuperscript{nd} run</td>
</tr>
<tr>
<td>100</td>
<td>1.3±0.17%</td>
<td>1.0±0.11%</td>
<td>7.9±0.53%</td>
<td>4.4±0.17%</td>
</tr>
<tr>
<td>200</td>
<td>6.0±0.54%</td>
<td>3.8±0.25%</td>
<td>33.1±0.55%</td>
<td>27.6±1.16%</td>
</tr>
<tr>
<td>300</td>
<td>3.1±0.25%</td>
<td>2.4±0.26%</td>
<td>28.6±0.48%</td>
<td>26.0±0.91%</td>
</tr>
</tbody>
</table>

Figure 4-17. A) Percent conversion of PE to PA; B) PHIP enhancement factor and pairwise selectivity over 10 mg 1% Pt/Silica Gel, 106 mg 4.2% Pt/Silica Gel, 113 mg Pt\textsubscript{3}Sn/Silica Gel and 87 mg PtSn/Silica Gel at different temperatures.
The mesoporous silica shell is expected to afford stability against aggregation and sintering effects, while not hindering access to the catalytic surface.\textsuperscript{22} To confirm that the systematic trend of total conversion and pairwise selectivity arises from the changing composition of Pt-Sn and not from the mSiO\textsubscript{2}, a series of catalysts supported on silica gel were tested under identical reaction conditions as the mesoporous silica shell encapsulated catalysts. While the supported pristine Pt catalyst yield significantly higher conversion as manifested by the intensive thermally polarized PA signal H\textsuperscript{a} (top panel of Figure 4-14) than the supported PtSn alloy catalyst, the supported PtSn alloy yield PHIP signals with comparable intensity (bottom panel of Figure 4-14). The conversion of PE and H\textsubscript{2} to PA follows the order 4.2\% Pt (28.6\%) $\gg$ 1\% Pt (3.1\%) $\gg$ Pt\textsubscript{-3}Sn (0.4\%) = PtSn (0.4\%) at 300 °C (Figure 4-17A and Figure 4-16), whereas the PHIP enhancement factor/pairwise selectivity follows the reverse order, PtSn (301/2.9\%) $>$ Pt\textsubscript{-3}Sn (181/1.7\%) $>$ 1\% Pt (23/0.2\%) $>$ 5\% Pt (6/0.06\%) (Figure 4-17B and Figure 4-15).
Figure 4-18. 400 MHz $^1$H NMR spectra obtained in a slurry reactor. A) PASADENA spectra obtained by para-hydrogenation of vinyl acetate in 2 mL d-methanol using 30mg of the mSiO$_2$ encapsulated catalyst at 5.6 bar and 80 °C. Each spectrum was obtained by a single FID. The inset shows an expansion of the spectra around the methyl group peaks. B) ALTADENA spectra obtained after bubbling n-H$_2$ (top) or p-H$_2$ through a slurry containing 2 mL water, 50 mg of Pt$_3$Sn@mSiO$_2$ catalyst, and dissolved 2-HEA at 5.6 bar and 120 °C.
Figure 4-19. 400 MHz $^1$H ALTADENA NMR spectra obtained by repeated bubbling p-H$_2$ gas through a slurry containing 2 mL water, 25 mg of Pt$_3$Sn@mSiO$_2$ catalyst, and dissolved 2-HEA at a pressure of 5.7 bar and temperatures of 120 °C for three times.

Figure 4-18A presents the PASADENA spectra of HP ethyl acetate after bubbling p-H$_2$ gas at 5.6 bar through d-methanol solutions of vinyl acetate and 30 mg of Pt@mSiO$_2$, Pt$_3$Sn@mSiO$_2$ or PtSn@mSiO$_2$. PASADENA antiphase multiplet patterns (peaks “a” and “b”) are clearly observed for the bimetallic catalysts but not seen in the case of monometallic Pt@mSiO$_2$. Pt$_3$Sn@mSiO$_2$ yielded the most intense PASADENA signals, reflecting a more optimal balance between conversion and pairwise selectivity for this catalyst at 80 °C, consistent with the results of PE dissolved in d-benzene, as presented in Figure 4-20. The results clearly demonstrate that the mSiO$_2$-encapsulated iNPs can direct pairwise addition to the dissolved substrates at a rate that is sufficiently high relative to spin-relaxation at this temperature. However, a reliable quantification of
the signal enhancement, pairwise selectivity and conversion was not possible due to the continuous reaction with dissolved hydrogen and possible para → ortho conversion of H₂ in the slurry.

Figure 4-20. 400 MHz ¹H PASADENA NMR spectra obtained by bubbling p-H₂ gas through a slurry containing 2.5 mL d-benzene, 20 mg of catalyst, and dissolved PE at a pressure of 5.6 bar and temperature of 80 °C. Each spectrum was obtained by accumulating 32 transients. An expansion of the spectra around the PA peaks is shown on the right.

Lastly, the efficacy of the Pt-Sn iNP catalysts in the aqueous phase is demonstrated. Hydrogenation of 2-hydroxyethyl acrylate (HEA) in D₂O was catalyzed by Pt₃Sn@mSiO₂ in the earth’s magnetic field. After bubbling p-H₂ gas through the slurry, the sample tube was immediately transferred into the 400 MHz NMR magnet and the ALTADENA NMR spectrum collected with a 90° pulse. As seen in Figure 4-18B and Figure 4-19, intense NMR signals of the methyl (c) and methylene (d) groups of 2-hydroxyethyl propionate (HEP) were obtained. Due to the continuous reaction in the slurry, a reliable determination of the PHIP signal enhancement was not available in these experiments. Moreover, an estimated factor of 10 loss of polarization occurs during the ~10 s transfer of the sample from low to high field. To ensure that this
hydrogenation occurs heterogeneously on the iNPs and not homogeneously by leached metal ions, as can occur in immobilized complexes,\textsuperscript{61} PHIP experiments were attempted using the supernatant obtained by decanting and centrifugation of the aqueous slurry containing the particles. As shown in Figure 4-21, no conversion and no PHIP NMR signals could be observed. Table 4-8 reports the Pt and Sn concentrations in the supernatant, as determined by ICP-MS analysis. The measured levels of 14.67 ppb (0.0001\% leached Pt) and 69.62 ppb (0.003\% leached Sn), respectively, are too low to catalyze any reaction.

![Diagram of 2-HEA and 2-HEP structures](image)

**Figure 4-21.** After three repeated bubbling experiments and the precipitation of the solid catalysts, the supernatant was decanted from the solution. Then the supernatant was centrifuged at 14000 rpm for 10 minutes, twice. P-H\textsubscript{2} were bubbled through the supernatant for 60 s under the same condition as the reactions with the catalysts loaded. 400 MHz \textsuperscript{1}H NMR spectra were acquired before (top), immediately after bubbling (middle) and after cooling to room temperature (bottom). The ratios of 2-HEP and 2-HEA were calculated based on the integrals of peak d and 5 of the spectra collected at room temperatures. Eight scans were collected for the room-temperature spectra with a recycle delay of 40s. A single scan was collected for the high-temperature spectrum.
Table 4-8. Concentration of Pt and Sn that was Leached into the Supernatant from Pt\textsubscript{3}Sn@mSiO\textsubscript{2} Analyzed by ICP-MS on Different Isotopes

<table>
<thead>
<tr>
<th>Sample</th>
<th>\textsuperscript{118}Sn (ppb)</th>
<th>\textsuperscript{120}Sn (ppb)</th>
<th>\textsuperscript{194}Pt (ppb)</th>
<th>\textsuperscript{195}Pt (ppb)</th>
<th>\textsuperscript{196}Pt (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt\textsubscript{3}Sn@mSiO\textsubscript{2}</td>
<td>69.62 (\pm) 0.20</td>
<td>69.93 (\pm) 0.23</td>
<td>13.05 (\pm) 0.16</td>
<td>12.49 (\pm) 0.30</td>
<td>14.67 (\pm) 0.06</td>
</tr>
</tbody>
</table>

**Hyperpolarized Singlet State**

One of the major limitations of hyperpolarization techniques for *in vivo* biomedical imaging is the short spin relaxation time, typically limiting to 1 to 2 mins.\textsuperscript{1} To probe longer biological processes, longer spin relaxation time of the hyperpolarized biomarkers is desirable. Parahydrogen is inherently a nuclear singlet with a spin relaxation time up to 4 months, depending on the storage media.\textsuperscript{39} Therefore, PHIP offers a more direct means of producing hyperpolarized long-lived spin states, compared to dDNP.\textsuperscript{62} Upon pairwise addition, the singlet order of the parahydrogen is preserved in the adduct molecule under suitable conditions, leading to long-lived hyperpolarized spin states. A growing list of long-lived molecules haven been demonstrated, including phenylacrylic acid ethylester, acrylic acid methylester\textsuperscript{63}, ethylene,\textsuperscript{64} propane,\textsuperscript{65-66} dimethyl maleate and fumarate.\textsuperscript{67-69} To convert the pure singlet order to observable magnetization, it requires to break the symmetry of the singlet state by chemical reactions,\textsuperscript{68, 70} field cycling or RF pulse sequence.\textsuperscript{56-58, 71-73} All the parahydrogen derived long-lived hyperpolarized molecules have been created by homogeneous catalysts so far, which faces the major challenge of catalyst extraction and incompatibility with continuous-flow production, with the only exception being the hyperpolarized propane gas molecule produced at low magnetic field over Rh NPs supported on titanates.\textsuperscript{65-66} Because of the small chemical shift difference between the methyl and ethyl protons relative to the *J*-coupling at low magnetic field, the so-called pseudo-singlet state was created, prolonging the spin relaxation time to 13.1s (spin-
lattice relaxation time $T_1$ is 3.9s). Nevertheless, propane molecule is neither a true singlet state and nor a biomolecule. In contrast, maleate and fumarate molecules are present in the TCA cycles and fumarate is a promising indicator of cancer treatment.\textsuperscript{74} Both molecules possess the symmetry property to preserve the singlet order in the vinylene group.\textsuperscript{58} Here, making use of the mesoporous silica encapsulated Pt-Sn iNPs, we prepared hyperpolarized long-lived maleate and fumarate molecules. The conversion of the singlet order into observable magnetization was achieved by level anti-crossing effect and a modified Spin Lock Induced Crossing (SLIC) pulse sequence.\textsuperscript{56-57, 69, 75}

**Conversion of singlet state by level anti-crossing state mixing**

![Conversion of singlet state by level anti-crossing state mixing](image)

Figure 4-22. $^1$H NMR spectra obtained by making use of level anti-crossing effect at waiting times of 25 min (top) and 1 min (bottom). A single scan was collected following a RF 90° pulse.
As presented in Figure 4-22 and Figure 4-23, hydrogenation of DMAC catalyzed by Pt₃Sn@mSiO₂ yield three products, DMM, DMF and DMS. The total conversion of DMAC with the two waiting times, 1 min and 25 mins in the ice bath were the same, calculated to 31.3%. The product selectivity is presented in Table 4-9. The negligible difference in total conversion and product selectivity indicates the immediate quenching of the reaction after immersion into the ice bath, as well as a good reproducibility of each reaction. Pt₃Sn@mSiO₂ is highly selective toward DMM with a selectivity of 83.4%.

Table 4-9. Product selectivity of DMM, DMF and DMS.

<table>
<thead>
<tr>
<th>Selectivity %</th>
<th>t_w = 1 min</th>
<th>t_w = 25 mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMM</td>
<td>82.8</td>
<td>83.9</td>
</tr>
<tr>
<td>DMF</td>
<td>4.4</td>
<td>4.1</td>
</tr>
<tr>
<td>DMS</td>
<td>12.8</td>
<td>11.9</td>
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</tbody>
</table>
While keeping the other experimental parameters the same, varying the waiting time in the ice bath at earth magnetic field is equivalent to varying the time that is allowed for relaxation of the singlet order in the product molecule. $^1$H NMR spectra of the product mixture acquired immediately after the sample loading are presented in Figure 4-22 with two waiting times of 1 min and 25 mins. Despite the same conversion and selectivity, the signal intensity of the -CH groups in DMM and DMF with a waiting time of 1 min is significantly stronger than that with a waiting time of 25 min. It confirms that the singlet order of p-H$_2$ was incorporated and preserved on the adduct molecules through pairwise addition, catalyzed by Pt$_3$Sn@mSiO$_2$ NPs.$^{56,76}$ Since the physical distance of level anti-crossing points of DMM (0.10T) and DMF (0.13T) in the magnet bore is shorter than the length of NMR sample, level anti-crossing happens for DMM and DMF simultaneously during the stop at the stray field of 0.1 T. The residual signals of H$_2$, H$_2$O and DMAC in the difference spectrum arise from the slightly different relaxation time of the thermally polarized signal as the sample transfer from 0.1 T to 9.4 T was manually performed.

It has been demonstrated that a transfer time of 5 s from 0.1 T to the observing field at 7 T is long enough to reach the maximum conversion of singlet to triplet state for DMM molecules.$^{59}$ A stop at 0.1T for 20 s was applied in our experiment to ensure the maximum conversion, at the expense of loss of magnetization from $T_1$ relaxation of the triplet states. Without precise control, measurement of $T_5$ is challenging due to variable $T_1$ relaxation during the sample transfer, as well as the calculation of PHIP enhancement factor. Therefore, multiple-conversion SLIC pulse sequence was applied to measure the $T_5$ of DMM.
Conversion of singlet state by multiple-conversion SLIC RF pulse sequence

The multiple-conversion SLIC pulse sequence was previously applied to measure the lifetime of DMM singlet created by PHIP using metal organic complex catalyst. The advantages of the multiple-conversion approach is that the $T_s$ measurement becomes independent of the initial signal intensity and thus the relaxation processes during sample transfer, according to Eq. (4-15), (4-16) and (4-17).

![Figure 4-24. $^1$H NMR spectra obtained by applying the multiple-conversion SLIC pulse sequence A) immediately and B) 25 mins after the NMR sample loading at $\Delta t = 40s$.](image)
Figure 4-25. $^1$H NMR spectra obtained by applying the multiple-conversion SLIC pulse sequence immediately after the NMR sample loading at $\Delta t$ of 30, 40, 50, 60, 80s.

Figure 4-24 and Figure 4-25 present the spectra acquired by applying the multiple-conversion SLIC pulse sequence immediately after sample loading. The PHIP signal of the vinylene group at 6.4 ppm is in emission phase and gradually decreases as the number of SLIC pulse increases. In contrast, in Figure 4-24B, 25 mins after the sample loading, only the residues of thermally polarized signal are visible, indicating the complete relaxation of the singlet state. Figure 4-26A presents the normalized signal as a function of pulse looping number $n$. Least square fitting of the data according to Eq. (4-17) yield the exponential decay rate $\lambda$ for a fixed value $\Delta t$. Figure 4-26B presents the least square fitting of $\lambda$ as a function of $\Delta t$. According to Eq. (4-17), the singlet lifetime $T_s$ is calculated to be $196.1 \pm 26.14$ s, which affords a 12-fold enhancement
compared to the $T_1$ spin relaxation time that was measured to be $16.9 \pm 0.02$ s, in agreement with the published value.\textsuperscript{57} The singlet lifetime that is close to the published value indicates that the transient adsorption of the intermediate and final product molecule on the Pt\textsubscript{3}Sn intermetallic surface has negligible effect on the spin relaxation lifetime of the singlet state.

![Graph A](image.png)

![Graph B](image.png)

Figure 4-26. A) normalized signal integrals of vinylene group as a function of pulse looping number $n$ with $\Delta t$s of 30, 40, 50, 60 and 80 s and the corresponding exponential fittings and B) Exponential decay rate $\lambda$ as defined in Eq. (4-17) as a function of $\Delta t$. Least square linear fitting yields a slope of $0.0051 \pm 0.00068$ and intercept with y-axis of $-0.01 \pm 0.04$.

The efficiency of the SLIC pulse is calculated to be 0-3 %, which is lower than the reported value $\sim 14\%$.\textsuperscript{57} As a 10 mm NMR tube with solid catalysts residing at the bottom was used in our experiment, compared to 5 mm NMR tube containing homogeneous liquid that was used in the literature, the reduced $B_0$ and $B_1$ homogeneity
could result in the lower efficiency of the pulse sequence in our experiments as the efficiency is highly sensitive to resonance offset.\textsuperscript{57, 69}

Summary

We have shown that the mSiO\textsubscript{2}-protected iNPs prepared by the seeded growth method are effective catalysts for producing PHIP NMR signals of hydrogenation adducts in the gaseous or solution phases. The mSiO\textsubscript{2} shell endows the iNPs with stability against aggregation, sintering and phase separation effects without totally obstructing the catalytic surface. Particle surfaces and metal compositions can be tailored to effectuate an increase in the pairwise selectivity of hydrogenation. The pairwise selectivity of $\varphi = 10.9 \pm 0.5\%$ obtained with 30 mg of PtSn@mSiO\textsubscript{2} at 300 °C is the highest to be reported for any heterogeneous NP catalyst and more than three orders of magnitude higher than for monometallic Pt@mSiO\textsubscript{2} NPs of similar size. Note that this is the observed $\varphi$ value, uncorrected for relaxation losses. The data is consistent with the elimination of the threefold Pt hollow sites where facile dissociative adsorption of H\textsubscript{2} occurs. Direct hydrogenation of the alkene, by either an Eley-Rideal or Langmuir-Hinshelwood channel, becomes relatively more important upon incorporation of Sn.\textsuperscript{77-78}

The high pairwise selectivity observed with PtSn@mSiO\textsubscript{2} was accompanied by low conversion, exemplifying the typical inverse relationship between selectivity and activity in catalysis. Nevertheless, $\chi$ was shown to scale linearly with PtSn@mSiO\textsubscript{2} mass and H\textsubscript{2} partial pressure up to 750 mbar, while $\varphi$ was unaffected, suggesting that larger amounts of catalyst and higher pressures would increase the conversion. Moreover, it should be noted that the particle sizes of our iNPs are relatively large (c.a.
>14 nm); hence the active metal dispersion is comparatively low. Current research is focused on the synthesis of small-diameter iNPs (c.a. <5 nm) which can be expected to deliver much higher conversion.

Hyperpolarization of 2-HEP in water is significant because this is the standard molecule for in vivo angiography studies. The mSiO₂ encapsulated metal particles afford spontaneous and rapid separation from the catalyst, making this catalyst platform intrinsically safer than dissolved or immobilized transition metal complexes or free-radical polarizing agents. Agents that have previously been demonstrated to be hyperpolarizable by homogeneous PHIP includes acetate and pyruvate, lactate and phospholactate, nicotinimide, and succinate. It can be expected that slurry reactions containing iNPs will be effective for parahydrogen induced hyperpolarization of many if not all of these substances.

We have shown that mSiO₂-encapsulated Pt₃Sn intermetallic nanoparticles is an effective catalytic platform to produce hyperpolarized long-lived dimethyl maleate and dimethyl fumarate simultaneously, with a high selectivity toward dimethyl maleate. A singlet lifetime of 196.1s in methanol-d₄ was obtained, which affords 12-fold enhancement of spin relaxation lifetime. The transient adsorption of the intermediate and product molecules on the Pt₃Sn intermetallic surface does not shorten the singlet lifetime, reference to the long-lived singlet created by homogeneous catalysts. Therefore, our study represents the first demonstration of hyperpolarized long-lived biomolecules produced by hetPHIP.
CHAPTER 5
SHAPED CERIA NANOCRYSTALS

Background

Well-defined shapes are useful in catalysis studies as they facilitate surface structure sensitivity investigations. Ceria nano-rods are terminated predominantly by {100} and {110} facets, nano-cubes by {100} facets, and octahedra by {111} terraces. The synthesis of nanocrystals with these three shapes allows investigation of the facet dependence of pairwise addition and replacement processes. Polycrystalline CeO$_2$ nanoparticles, which expose mainly {111} terraces, are significantly more active than CeO$_2$ nano-cubes with {100} surfaces. This is attributed to differences in the oxygen vacancy density on the various CeO$_2$ facets. High energy CeO$_2$ {100} and {110} surfaces (rods and cubes) have more oxygen vacancies that promote oxidation reactions, while low-energy, low-vacancy {111} surfaces favor hydrogenation.

Ceria is among several polycrystalline metal oxides that have been reported to yield PHIP signals using PE as substrate, although a temperature of 600 °C was apparently required. Kovtunov et al. briefly mentioned a PHIP effect for ceria but did not include presentation of any PHIP spectra, and hydrogenation of PY was not studied for this catalyst. Investigation of PE and PY hydrogenation over CeO$_2$ nanocrystals with well-defined surface facets using PHIP NMR has never been reported.

In a recent DFT study, hydrogenation of PE and PY were investigated over a CeO$_2$ {111} surface. The high selectivity of semi-hydrogenation of PY to PE was explained by the exothermic adsorption of PY and endothermic adsorption of PE on this surface as well as the different reactivity of intermediate species. Only the stepwise transfer of H atoms, similar to a Horiuti-Polanyi type mechanism, was considered in
this study, and this would not favor preservation of the proton spin correlation in parahydrogen. In another DFT study, the reaction thermodynamics of PE and PY hydrogenation on a fully hydroxylated \{111\} terminated CeO$_2$ surface was investigated under high H$_2$:alkyne reactant conditions.$^{85}$ On this surface, calculations indicated that hydrogenation of PY occurs through a low energy six membered ring transition state involving the H-H bond, the adsorbed alkyne and adjacent hydroxyl group. While this transition state does not result in pairwise addition, since one H atom is transferred to the substrate from H$_2$ and the other from OH, pairwise addition can occur via a four-membered ring transition state, though the activation energy is predicted to be significantly higher on the fully hydroxylated surface.$^{85}$ Distinguishing pairwise and non-pairwise paths is readily achieved by PHIP NMR and is the focus of this section.

**Materials Synthesis and Characterizations**

**CeO$_2$ Nanocrystal Synthesis**

CeO$_2$ nanocrystals were synthesized using the hydrothermal method reported by Overbury and coworkers.$^{86}$

For CeO$_2$ nano-octahedra, 0.0076g of Na$_3$PO$_4$·12H$_2$O (Fisher Scientific, Certified ACS) and 0.868g of Ce(NO$_3$)$_3$·6H$_2$O (ACROS, 99.5%) were dissolved in 80 mL of deionized water in a Teflon beaker. The mixture was covered and stirred at room temperature for 30 minutes, before the Teflon beaker was inserted into the autoclave. The magnetic stir bar was removed and the autoclave sealed and heated to 170 °C at which temperature it was held for 24 hours.

For CeO$_2$ nano-rods and nano-cubes, 0.868 g of Ce(NO$_3$)$_3$·6H$_2$O was dissolved in 10 mL of deionized water in a Teflon liner. In a separate beaker, 9.6 g of NaOH (Sigma-Aldrich, 99.99%) was dissolved in 70 mL of water. The NaOH solution was
cooled to room temperature and then added slowly to the aqueous solution of cerium nitrate in the Teflon liner. Upon mixing, the solution changed color from transparent to light purple. The resulting mixture was stirred for 30 minutes, before the stir bar was removed, and the Teflon liner inserted into the autoclave. The autoclave was then sealed and heated at 100 °C for nano-rods and 180 °C for nano-cubes at which temperature it was held for 24 hours.

For the synthesis of all three shapes, a white precipitate of nanocrystals was observed at the bottom of the liner after the hydrothermal reaction. The precipitates were separated from the liquid by centrifugation and the solid collected by decanting the liquid. The solids were re-suspended in water under ultra-sonication for 30 minutes, and then separated again using centrifugation. This process was repeated a total of three times. The particles were then suspended in ethanol under ultrasonication and recovered by centrifugation using the same procedure, which was repeated three times. After the last centrifugation, the recovered white solids were dried in a crucible at 105 °C overnight and then calcined at 350 °C for 3 hours.

**Transmission Electron Microscopy**

The transmission electron microscopy (TEM) images were collected using a JEOL 2010F TEM instrument with an operating voltage of 200 kV. The images were taken in high-resolution mode using a Gatan Orius SC200B camera. For the preparation of the TEM Grids, the solids were suspended in ethanol with a concentration of approximately 5 mg/mL. Upon fully suspending the particles using ultrasonication, a small droplet (10 µL) of the solution was placed on a 400 mesh copper on carbon grid.
**X-ray Diffraction Analysis**

The XRD data were gathered on a Panalytical Xpert Powder instrument using Bragg-Brentano geometry with Cu-Kα radiation (λ = 1.54 Å). The XRD patterns were recorded in a 2θ range from 15° to 80° at ambient conditions. In all cases, the diffraction patterns were obtained after the calcination treatment of the samples (heating at 350 °C for 3 hours).

**BET Surface Area Analysis**

Brunauer-Emmett-Teller (BET) surface area measurements were performed on a NOVA 1200 instrument under liquid N₂ environment using a 6-point isotherm with $R^2 > 0.99$. The samples and the sample holders were dried in an oven at 105 °C overnight before the measurements.

**Specific Surface Area**

For comparisons with the measured BET surface areas, specific surface areas for each shape were calculated from the distribution of nanocrystal dimensions estimated by analysis of the TEM images and the density of ceria. Histograms of the nanocrystal dimensions for each shape, shown in Figure 5-1, were constructed from the analysis of 100 particles for octahedral and rods. For cubes, 200 particles were analyzed due to the broader size distribution. The least-squares fits of the histograms, assuming a Gaussian distribution function, are shown by the solid curves superimposed on each histogram. Specific surface areas were estimated using the following formulas.

$$\bar{A}_{oct} = \frac{2\sqrt{3}}{(\sqrt{2}/3)\rho_{ceria}} \int_{0}^{\infty} \frac{i^2 P_i(l) \, dl}{\int_{0}^{\infty} i^3 P_i(l) \, dl}$$  (5-1)
Here, $P_l(l)$ and $P_w(w)$ are the (normalized) edge length and width distribution functions. For rods, a square prism shape was assumed. The density of ceria $\rho_{\text{ceria}}$ was taken as 7.65 g/cm$^3$. Average edge length or width and standard deviations are reported in Figure 5-1.

Figure 5-1. Histograms of the nanocrystal dimensions for each CeO$_2$ nanocrystal shape: A) Octahedra B) Cubes C) Rods (length distribution) D) Rods (width distribution). There is no apparent correlation between rod width and length. The average and standard deviation from the least-squares fit to a Gaussian distribution is indicated in each panel. The fits are shown as the solid curves.
Reaction Rate

Reaction rates were calculated using Eq. (5-4) where \( r_{\text{area}} \) denotes reaction rate per unit surface area of the ceria nanocrystals. Density of propene \( \rho_{\text{PE}} \) was taken as 1.77 kg/m\(^3\) at 21.1 °C and pressure of 1 atm.\(^8\) Flow rate of propene \( r_{\text{flow}} \) was 20 mL/min. Signal integrals were taken from the static thermally polarized spectra after cubic spline baseline correction. All peak integrations were repeated three times on the same peak with slightly different choice of points for baseline correction to take into account the errors which arise from low signal-to-noise ratio for certain peaks. Average values were used for calculations.

\[
r_{\text{area}} = \frac{\rho_{\text{PE}} r_{\text{flow}}}{M_{\text{PA}} m_{\text{ceria}} \bar{A}_{\text{ceria}}} \left( \frac{S_{\text{therm}}^{\text{therm}}}{S_{\text{PA,CH}_3}^{\text{therm}}} / 2 \right) + \frac{S_{\text{therm}}^{\text{therm}}}{S_{\text{PE,CH}_3}^{\text{therm}}} (5-4)
\]

where

\( S_{\text{PA,CH}_3}^{\text{therm}} = \) thermally polarized NMR signal integral of the propane methyl group.

\( S_{\text{CH}_3,\text{PE}}^{\text{therm}} = \) thermally polarized NMR signal integral of the propene methyl group.

\( M_{\text{PA}} = \) molar mass of propane.

\( m_{\text{ceria}} = \) experimental mass of catalyst.

\( \bar{A}_{\text{ceria}} = \) specific surface area of the catalyst.
NMR Spectroscopy

The details of the ALTADENA hydrogenation reactor setup were described in Chapter 3. Spectra of the reaction product flow were acquired on a Bruker Avance 400 MHz \( (B_0 = 9.4 \text{ Tesla}) \) NMR spectrometer 30 seconds after the start of the reaction. ALTADENA and thermally polarized NMR signals were signal averaged using either 16.5 \( \mu s \) 90° or 7.7 \( \mu s \) 42° pulses. 32 transients were accumulated using a recycle delay of 2 s. The ALTADENA difference spectra presented in all related figures were obtained by subtracting spectra acquired with n-H\(_2\) (25% parahydrogen) from the spectra with p-H\(_2\) (50% parahydrogen). The residual broad peak due to o-H\(_2\) content of the unreacted H\(_2\) gas, which is different in p-H\(_2\) and n-H\(_2\), was removed from the difference spectrum by incorporation into the cubic spline baseline correction. To acquire the fully thermally polarized NMR spectra, valves on the inlet and the outlet to the NMR tube were simultaneously sealed shortly after acquisition of spectra under flowing conditions. A total of 256 signal transients were accumulated with a recycle delay of 5s. The residual broad peak due to unreacted H\(_2\) gas was removed by cubic spline baseline correction. Line broadening of 8 Hz is applied to all spectra. Signal enhancement factors were calculated as described in Chapter 2.

Density matrix simulations. Six spin density matrix simulations were performed using SpinDynamica v2.8.3.\(^{88,7}\) The 0.45 s time-of-flight was used to calculate the field ramp.

Results and Discussion

Hydrogenation of Propene

Shaped CeO\(_2\) nanocrystals with surfactant-free surfaces were synthesized by the hydrothermal method.\(^{86,89-90}\) With a cubic fluorite crystal structure, ceria nano-rods are
enclosed predominantly by (110) and (100) facets, nano-cubes by (100) facets and nano-octahedra by (111) facets. Views of these three facet planes are presented in Figure 5-2. The calculated oxygen vacancy formation energies follow the order (111) > (100) > (110). Consequently, the surface oxygen density of the three shapes follows the order nano-octahedra > nano-cubes > nano-rods. It has been proposed that surface oxygen stabilizes adsorbed hydrogen species, thus promoting hydrogenation reactions. Transmission electron micrographs (TEM) are presented in Figure 5-3 and Figure 5-5. The High Angle Annular Dark Field-Scanning Transmission Electron Microscopy (HAADF-STEM) images shown in Figure 5-4 reveal the atom arrangements on the facets of nano-rods and nano-octahedra. Analysis of the images of the rods confirmed the prevalence of (110) and (100) facets with the majority of rods exhibiting large (110) surfaces. Consistent with a high oxygen vacancy density, the (110) facet of the nano-rods exhibits a rough appearance with dark “pits” (Figure 5-4A and C). These regions have fewer Ce atoms and are therefore possibly accompanied by oxygen vacancies. In contrast, the nano-octahedron is enclosed by essentially defect-free (111) crystalline facets, as seen in Figure 5-4D and F, and this shape provides the greatest density of surface oxygen anchoring sites for hydrogen chemisorption. Crystallinity was confirmed by X-ray diffraction (Figure 5-6). All three shapes are formed with a cubic fluorite structure. The measured Brunauer-Emmett-Teller (BET) surface areas of the nano-rods, nano-cubes, and nano-octahedra samples are 60 m²/g, 21 m²/g and 4 m²/g, respectively. The specific surface areas estimated from the nanocrystal size distributions determined from analysis of the TEM images are 71 m²/g, 30 m²/g , and 2.3 m²/g, respectively, in reasonable agreement with the BET surface area.
measurements. Reaction rates were normalized to the BET surface area to facilitate comparison of the activities of different surface facets. This approach was established in previous studies of the facet dependence of oxidation and hydrogenation over ceria.\textsuperscript{80, 82, 95} The reactant gases, H\textsubscript{2} (normal or para-enriched) and PE (or PY) were fed into the reactor at flow rates of 600 mL/min and 20 mL/min, respectively. The PHIP experiments were performed in ALTADENA\textsuperscript{76} mode, where hydrogenation products formed at 5 mT are transported adiabatically to 9.4 T for NMR detection.

![Atomic arrangement of (111), (100), and (110) facet planes of CeO\textsubscript{2}. Created with CrystalMaker\textsuperscript{®}.](image)

Figure 5-2. Atomic arrangement of (111), (100), and (110) facet planes of CeO\textsubscript{2}. Created with CrystalMaker\textsuperscript{®}. 
Figure 5-3. TEM images of A) CeO\textsubscript{2} nano-octahedra, B) nano-cubes and C) nano-rods. Structural models of D) CeO\textsubscript{2} nano-octahedron, E) nano-cube and F) nano-rod simulated by CrystalMaker®. Materials synthesized by Dr. Haibin Zheng from University of Florida. Reproduced with permission from ref. 60 © John Wiley & Sons, Ltd., 2015.
Figure 5-4. STEM images of nano-rod and nano-octahedron. A) High magnification of the nano-rod; B) FFT pattern from A) showing a [110] orientation diffraction pattern; C) Low magnification of the nano-rod; D) High magnification of the nano-octahedron; E) FFT of D) showing a [110] orientation diffraction pattern; F) Low magnification of the nano-octahedron.

Figure 5-5. TEM images of CeO$_2$ A) nano-octahedra, B) nano-cubes and C) nano-rods on a large field of view. The images show the uniformity of the as-synthesized CeO$_2$ nanocrystals.
In the hydrogenation of PE with 50% para-enriched hydrogen (p-H₂) at temperatures ranging from 150 to 300 °C, all three shapes produced intense ALTADENA-enhanced PA NMR signals (Figure 5-7 and Figure 5-8). The signal enhancement and the rate of conversion of PE into PA (Figure 5-9) were calculated from the fully relaxed, thermally polarized NMR spectra that were acquired on aliquots of reactor effluent (Figure 5-10). The 256 signal transients were accumulated using a recycle delay of 5 s.
Figure 5-7. 400 MHz $^1$H NMR spectra (90° RF pulse flip angle) acquired on the flowing reactor effluent gas resulting from a reactant gas mixture of PE and p-H$_2$ at a reactor temperature of 375 °C. A) CeO$_2$ nano-octahedra, B) CeO$_2$ nano-cubes or C) CeO$_2$ nano-rods. 32 signal transients were acquired with a 2 s recycle delay. Inset: Expansion of PE CH$_2$ (H$^d$ and H$^e$) spectral region.

Figure 5-8. ALTADENA spectra of product gas mixture of PE hydrogenation acquired at different temperatures catalyzed by A) nano-octahedra, B) nano-cubes and C) nano-rods. Each spectrum was acquired by accumulation of 32 transients.
Figure 5-9. A) Temperature dependence of the rate of PE hydrogenation, calculated from the PA and PE \( \text{CH}_3 \) peak integrations, normalized to the BET surface areas. B) ALTADENA NMR signal enhancement and pairwise selectivity for the hydrogenation of PE to PA based on the ratio of the ALTADENA and thermally polarized Ha NMR integrals.

Figure 5-10. Thermally polarized spectra resulting from PE hydrogenation at different reactor temperatures catalyzed by A) nano-octahedra, B) nano-cubes and C) nano-rods. Each spectrum was acquired by accumulation of 256 transients. Thermally polarized spectra of the static (non-flowing) gas mixture were acquired by sealing the inlet and outlet of the NMR tube simultaneously immediately after acquiring the thermally polarized spectra of the flowing gas.
At all temperatures, enhancement factors for rods, cubes, and octahedra were found to be the same, within experimental uncertainty. For example, at 375 °C, all shapes yielded an enhancement factor of $\approx 40$, corresponding to a pairwise selectivity of $\approx 2.4\%$. This is comparable to the value observed for hydrogenation of PE over supported Pt and Ir, where hydrogenation occurs mainly by the stepwise (Horiuti-Polanyi) mechanism. Hence, despite substantial differences in total catalytic activity, no significant facet dependence of the signal enhancement/pairwise selectivity was observed. The enhancement remained nearly temperature independent between 150 to 300 °C and then increased abruptly from $\approx 5$ to $\approx 40$ at 375 °C, indicating that pairwise addition is thermally activated. In contrast, the total reaction rate exhibited the opposite trend over the same temperature interval (300-375 °C), indicating that pairwise and random addition to the alkene occur via different reaction pathways.

Aside from the PA signal enhancements stemming from pairwise addition to PE, all three CeO$_2$ shapes also produced intense ALTADENA signals on all protons of PE (Figure 5-7). These signals are attributed to a pairwise replacement (PR) process, where two protons of the substrate are replaced with two protons from the same para-hydrogen molecule.$^7$ PR-PHIP is akin to SABRE,$^{96}$ in which the para-hydrogen spin order is incorporated into the substrate molecule with no net change in molecular structure. Figure 5-11 presents the ratios of the H$_f$ multiplet of PE (resulting from PR-PHIP) to the H$_a$ multiplet of PA (resulting from pairwise addition). For all three nanocrystal shapes, the PE/PA signal ratio is seen to increase monotonically with temperature. The signal ratio of approximately 0.7, which was achieved for nanorods
and nano-octahedra at 375 °C, is approximately three times greater than the highest ratio observed for supported metal nanoparticles.97

![Figure 5-11](image)

Figure 5-11. Temperature dependence of the PE/PA ALTADENA signal ratio over nano-rods and nano-octahedra, where PE is polarized by pairwise replacement catalysis. Black triangles: nano-rods. Blue disks: nano-octahedra. Green Square: nano-cubes.

In the hydrogenation of PY, intense PE ALTADENA signals were also observed for all catalyst shapes. However, no trace of PA formation is evident in the ALTADENA or thermally polarized NMR spectra (Figure 5-12 and Figure 5-13). This finding is due to the well-known selectivity of the semihydrogenation of PY to PE over CeO$_2$.82,92 The spectrum of thermally polarized PE formed by the reaction of PY with normal hydrogen ($n$-H$_2$) over cube-shaped ceria nanocrystals at 300 °C is shown in Figure 5-12a. At 300 °C and 50% para-enrichment, we obtained an enhancement factor of 150.7 based on three independent measurements using the ceria cubes. The enhancement factors for the other two shapes were not determined owing to insufficient signal-to-noise ratios of the thermally polarized PE resonances (because of the smaller surface area of the ceria octahedra and the lower activity of the ceria rods compared with the ceria cubes).
Figure 5-12. 400 MHz $^1$H NMR spectra (90° RF pulse flip angle) of products resulting from PY hydrogenation over shaped ceria nanocrystals. A) Thermally polarized spectrum of the products of hydrogenation over ceria nanocubes with n-H$_2$ at 300 °C. Note the eightfold amplification of the vertical scale relative to the other spectra in this Figure. Peak i was assigned to an alkadiene, as reported previously.$^{92}$ B) ALTADENA spectrum (32 scans) resulting from hydrogenation over nanocubes at 300 °C using p-H$_2$. C–E) ALTADENA spectra acquired for the hydrogenation over nanocubes (C), nano-octahedra (D), or nanorods (E) at 375 °C with p-H$_2$. Inset: Expansion of the PE CH$_2$ (H$^d$ and H$^o$) region exhibiting syn addition stereoselectivity.

Figure 5-13. ALTADENA spectra of product gas mixture of PY hydrogenation acquired at different temperatures catalyzed by A) nano-octahedra, B) nano-cubes and C) nano-rods. Each spectrum was acquired by accumulation of 32 transients. Hyperpolarized PE without any presence of the detectable PA were produced at all tested temperatures on both shapes, attributed to high selectivity of partial hydrogenation by CeO$_2$.$^{92}$
Figure 5-14. Simulated propene ALTADENA spectra for A) syn and B) anti pairwise addition to propyne using a 90° read pulse angle.

Insights into the mechanism of the pairwise addition to PY and the pairwise replacement in PE could be gleaned from the stereoselectivity of these processes, because the ALTADENA spectrum of PE is sensitive to the stereoselectivity of the addition/replacement. Based on the geometry of the transition state, the concerted addition to PY was predicted to occur in a syn fashion. By comparing the experimental spectrum to the spectral simulations for the cis and trans dispositions of the para-hydrogen spin order (Figure 5-14), the stereoselectivity could be determined. The experimental spectra obtained for all three shapes (Figure 5-8 and Figure 5-13) indicate syn addition to PY and syn pairwise replacement in PE. The stereoselectivity of the pairwise replacement process and the temperature dependence of the PE/PA ratio are consistent with the two-step dehydrogenation–rehydrogenation mechanism reported for supported metal nanoparticles.

Calculations of the pairwise selectivity of PY hydrogenation must account for the reduction in the ALTADENA polarization that is due to sharing of the spin order with ancillary protons not originating from H₂. The reduction, which is different for the cis and
trans dispositions of the bilinear spin order, was determined by numerical density operator calculation (See Chapter 2). Based on an estimated 90% syn addition stereoselectivity, the signal enhancement factor on PE at 300 °C corresponds to a pairwise selectivity of 2.7 ± 0.1%.

**Semihydrogenation of Propyne**

Hydrogenation of PY over the CeO$_2$ {111} surface was the subject of a recent DFT study at high H$_2$/PY ratios where the resting state of the catalyst is fully hydroxylated and all Ce$^{4+}$ ions are reduced to Ce$^{3+}$. For PY hydrogenation, two distinct concerted reaction paths were evaluated and compared to the ordinary stepwise addition path that is well known for alkene hydrogenation. The three paths and their associated transition states are sketched in Figure 5-15.

![Figure 5-15](image-url)

Figure 5-15. Simplified reaction paths for hydrogenation of PY over a CeO$_2$ {111} facet, as determined from DFT calculations, and implications to the pairwise and non-pairwise semihydrogenation of propyne. A) Stepwise addition. B) Six-membered ring transition state. C) Four-membered ring transition state (TS). Red: oxygen, large yellow: cerium, black: H atom in random proton spin state, blue with asterisk: proton derived from singlet (p-H2) state. Optimized charge density structures of the transition states can be seen in Figure 2 of Ref. Reproduced with permission from ref. © John Wiley & Sons, Ltd., 2016.
With the lowest activation energy (1.9 eV), the six-membered ring transition state (Figure 5-15B), consists of two C atoms of the adsorbed PY molecule, both H atoms of an adsorbed H₂ molecule, and a hydroxy group. Since one H atom is transferred from an H₂ molecule and the other from –OH in a concerted process, this kinetically favoured path results in non-pairwise addition with complete loss of parahydrogen spin order yielding zero PHIP NMR signal. The four-membered ring transition state incorporating two C atoms of PY and an adsorbed H₂ molecule (Figure 5-15C) would facilitate pairwise addition by direct saturation, but with a calculated activation energy of 3.43 eV, this would be only a minor path. Semihydrogenation of PY can also occur by a stepwise H atom transfer, as in the Horiuti-Polanyi (HP) mechanism (Figure 5-15A). The activation barrier for this path is estimated at ~3 eV (calculated for acetylene). Our previous study of propene (PE) hydrogenation showed that stepwise addition yields a facet-independent 2-3% pairwise selectivity over CeO₂. Since the lowest energy transition state for PY hydrogenation is one that promotes purely random addition, it follows that any NMR signal enhancement that might be observed in the PHIP spectrum must originate from either stepwise addition or concerted addition via the four membered ring transition state.

The aforementioned DFT study identifies qualitatively different mechanisms for hydrogenation of PE and PY. Hydrogenation of PE to propane (PA) occurs via stepwise addition with a calculated barrier of around 2.7 eV which is considerably higher than the concerted path of PY hydrogenation through the six membered ring. This accounts for the high selectivity of semihydrogenation (i.e. PY hydrogenation to PE without PA formation). Formation of a four or six membered ring transition state incorporating PE
(instead of PY) is frustrated by the presence of two additional H atoms on the adsorbed alkene, allowing hydrogenation to occur only by stepwise addition. In the regime of the low pairwise selectivity observed in hydrogenation of PE to PA, the pairwise selectivity is well-approximated as the ratio of the pairwise and non-pairwise addition rates. Observation of the same pairwise selectivity for ceria rods, cubes, and octahedra implies that both pairwise and random addition share the same dependence on the surface oxygen density. It follows that all PA product molecules (pairwise+non-pairwise) are formed via the same step-wise addition path. In contrast, hydrogenation of PY can also occur by either of two additional concerted reaction paths (Figure 5-15B and C): one involving surface oxygen that is intrinsically non-pairwise, and the other that is pairwise and oxygen-independent. This suggests that the pairwise selectivity for hydrogenation of PY should be facet dependent, unlike PE.

Figure 5-16 presents the thermally polarized 400 MHz $^1$H NMR spectra of the hydrogenation reactor effluent acquired for each of the three CeO$_2$ nanocrystal shapes using a 30:1 H$_2$:PY reaction mixture and a reactor temperature of 300 °C. Note that the selectivity of semihydrogenation of PY is close to 100% for all three shapes. Following the same trend as observed using acetylene as substrates, the overall rate of PY hydrogenation (normalized to surface area) at all reaction temperatures was highest over octahedra followed by cubes and then rods (Figure 5-18A). Due to differences in total surface area, catalytic conversion of PY to PE (per unit weight of catalyst) is highest over cubes, followed by rods and then octahedra. Isomerization of PY to propadiene (PD), evidenced by peak g in the thermally polarized spectra (Figure 5-16 and Figure 5-17), occurs as a side reaction. The selectivity toward PD vs. PE (Figure
5-18B) is strongly shape-dependent following the order rods >> cubes > octahedra. At 350 °C, the PD was the main product obtained with rods (86.2%), while octahedra yielded 95% PE. This PD selectivity is higher than the previously reported value for CeO$_2$ despite the lower temperature used here. The nanocrystal shape dependence of the product distribution (PE vs. PD) suggests that surface oxygen species mediates the branching between isomerization vs. hydrogen addition. Octahedral nanocrystals, which present the highest surface oxygen density and adsorb the largest number of H atoms in the vicinity of the adsorbed PY molecule, favor hydrogen addition while suppressing isomerization. In contrast, the abundant surface oxygen vacancies on rods increase the distance between an adsorbed PY molecule and adsorbed H atoms, thereby inhibiting the formation of a six-membered ring transition state. Instead, an electron pair migrates from the triple bond to the adjacent carbon-carbon bond. For all three CeO$_2$ shapes, isomerization increases as reaction temperature increases, consistent with a higher activation energy for isomerization relative to addition.
Figure 5-16. 400 MHz $^1$H NMR spectra (90° RF pulse) of products resulting from PY hydrogenation over shaped ceria A) nano-rods, B) nano-cubes, C) nano-octahedra at $p$-$H_2$ and PY flow rates of 600 mL/min and 20 mL/min, respectively, at 300 °C. Upper traces: thermally polarized spectra. Lower traces: ALTADENA hyperpolarized spectra (32 transients) obtained using $p$-$H_2$. Note the 32x (1024 transients) and 8x (256 transients) expansions of the vertical scales relative to the other spectra shown in this figure. Peak g is assigned to PD.

Figure 5-17. 400 MHz $^1$H NMR thermally spectra (90° RF pulse flip angle) of products resulting from PY hydrogenation over shaped ceria nanocrystals. Flow rates: PY 20 mL/min, $H_2$ 600 mL/min. A recycle delay of 5s was applied. 640 transients were accumulated for spectra collected at 250 °C. 1024 transients were accumulated for spectra collected at 300 °C and 350 °C except for cube at 300 °C (256 transients).
The pairwise selectivity of PY hydrogenation over each of the three ceria nanocrystal shapes was examined by continuous-flow ALTADENA-PHIP NMR spectroscopy. In the hydrogenation of PY with 50% para-enriched hydrogen (p-H₂) at 300 °C and 350 °C, all three shapes produced intense ALTADENA-enhanced PE NMR signals (peaks a-d in Figure 5-16), in contrast to the weak thermally polarized PE NMR signals that required copious averaging to be detected. Signal enhancement is calculated as the ratio of PE –CH peak in the ALTADENA NMR spectrum over that of the thermally polarized NMR spectrum, and pairwise selectivity is proportional to enhancement. The pairwise selectivities reported in Figure 5-18C have been corrected for spin relaxation and the effect of sharing of hyperpolarization to ancillary protons of
the PE molecule. For all three shapes, pairwise selectivity is found to be temperature-dependent. It is almost negligible at 250 °C, maximizes at 300 °C and then decreases at 350 °C. At 300 °C, pairwise selectivities of 8.1 ± 0.5% on rods, 2.6 ± 0.2% on cubes, and 1.6 ± 0.5% on octahedra (assuming 90% syn addition) were obtained. Clearly, distinct surface chemistry on the various facets renders significantly different pairwise selectivities. The pairwise selectivity obtained with ceria rods is slightly higher than the highest previously reported value for hydrogenation over any supported metal or metal oxide catalyst.

Note that although rods and cubes produced similar PHIP signal intensities (compare resonances a-d in Figure 5-16A and B), the signal enhancement is higher for rods where the thermally polarized signal is a factor of ~3 smaller. It is interesting to consider if the selectivity of isomerization to PD, which is highest for rods, could affect the PHIP signal enhancement on PE. If isomerization removes PY as a substrate proportionally from both pairwise and non-pairwise hydrogenation, then the NMR signal enhancement factor will be unaffected by the side reaction. Since pairwise selectivity of PY hydrogenation exhibits the same trend in the surface facet structure dependence as the selectivity toward PD, it is clear that surface oxygen plays a role in both processes. Rods, with the lowest oxygen density yield the highest pairwise selectivity, while octahedra, which present the highest surface oxygen density, yield the lowest.

The dependence of the pairwise selectivity on catalyst shape indicates varying relative contributions of the stepwise and concerted addition paths. On the {111} surface facets of the octahedra, conversion of PY to PE is dominated by non-pairwise hydrogenation through the low energy six-membered ring activated complex
incorporating a hydroxy group (Figure 5-15B). Consistent with the drastically reduced
catalytic activity over the cubes and rods, the {111} facet is most likely the only CeO$_2$
surface in which the surface oxygen atoms are sufficiently close or in the required
geometry to accommodate formation of this transition state. The pairwise contribution to
the propene adduct must stem from either the pairwise fraction of the stepwise addition
of hydroxy H atoms or from the direct saturation involving molecular H$_2$ bound to the
Ce$_{3+}$ sites via the four membered ring transition state, neither of which is kinetically
favored on the CeO$_2$ {111} surface but become relatively more important on the {110}
and {100} surfaces.$^{85}$ The facet dependence of the pairwise selectivity of PY
hydrogenation is explained by the different dependences of the pairwise and non-
pairwise reaction paths on the surface oxygen density and surface atom arrangement.
The facet structure dependence of the activation barriers for stepwise addition and
direct saturation of PY over CeO$_2$, which have not been calculated for the {110} and
{100} surfaces, may also affect the relative contribution of these two paths.

**Summary**

In summary, intense ALTADENA PHIP signals have been observed for the
hydrogenation of PE and PY using octahedral, cubic, or rod-shaped CeO$_2$ nanocrystals.
For PY as the reactant, hyperpolarized PE was produced by stereoselective semi-
hydrogenation, with no detectable formation of PA. The pairwise selectivities for alkene
and alkyne hydrogenation over CeO$_2$ nanocubes at 300 °C are similar. By using 99%
para enrichment and eliminating sharing of the parahydrogen spin order with ancillary
spins (e.g., by perdeuteration of PY), we project a signal enhancement of 850 with this
catalyst relative to the thermally polarized signal at 298 K and 9.4 T, corresponding to a
nuclear spin polarization of approximately 2.7% on the PE CH proton.
The low pairwise selectivity of PY hydrogenation is consistent with the Horiuti–Polanyi mechanism or the DFT predicted concerted addition involving the PY triple bond, a hydroxy group, and \( \text{H}_2 \) in a six-membered ring.\(^8\) The low pairwise selectivity of PE hydrogenation is the same for all three shapes and is similar to that observed on supported metal nanoparticles.\(^3\), \(^\text{103} \) All shapes were also found to efficiently catalyze pairwise replacement on PE. The \textit{syn} replacement stereoselectivity points to a two-step pairwise replacement process like the one that was reported for supported Pt and Ir catalysts.\(^9\)

We have presented the first investigation of a facet effect on the pairwise selectivity of alkene hydrogenation over a crystalline heterogeneous catalyst. Given that the rate of hydrogenation over ceria is strongly facet-dependent, it seemed plausible that the (100), (110), and (111) surfaces would lead to different pairwise addition selectivities towards PE, but this is not the case. Both random and pairwise addition pathways exhibit the same dependence on the oxygen vacancy density. However, the different temperature dependences for random and pairwise addition are indicative of distinct roles of the oxygen vacancies in these processes. Clearly, para-hydrogen-enhanced NMR spectroscopy can serve as a unique method to explore concerted hydrogenation and pairwise replacement reactions in these catalytic systems.

We have combined shape-selective nanocrystal synthesis with PHIP NMR spectroscopy to elucidate the mechanism of heterogeneous hydrogenation of an alkyne over reaction path for semihydrogenation of propyne over ceria \{111\} proceeds via a low energy six membered ring transition state. Confirming this prediction, the essentially defect-free \{111\} surfaces yield a low pairwise selectivity of only 1.6% while the
relatively high pairwise selectivity of 8.1% observed for nano-rods implicates direct saturation via a 4 membered ring transition state. The relative contribution of each path depends on the oxygen densities presented on the various facets of the ceria nanocrystal shapes. The general approach demonstrated in this work has excellent potential for the optimization of PHIP signal enhancement using heterogeneous catalysis which is suitable for the production of contaminant free hyperpolarized liquids and gases for biomedical utilization.
BACKGROUND

In strong metal-support interaction, a term introduced by Tauster, the cations of the support are reduced in the presence of H\textsubscript{2} at elevated temperatures. The concomitant loss of anions of the support facilitates approach of the metal atom toward the reduced cation, facilitating electron transfer from the d-orbitals of the reduced cation to the metal. For TiO\textsubscript{2}, SMSI can be accompanied by migration of TiO\textsubscript{x} over the surface of the metal, resulting in encapsulation and a geometrical blocking effect for adsorbates which can significantly affect the dissociative chemisorption of H\textsubscript{2}, thereby affecting the activity of hydrogenation catalysis. Hence, SMSI might also be expected to affect the pairwise selectivity in hydrogenation reactions. Indeed, a recent report demonstrated the effect of H\textsubscript{2} reduction of Pd/TiO\textsubscript{2} at 500 °C on the pairwise selectivity of 1,3-butadiene hydrogenation over this catalyst. Unfortunately, both the overall activity and the pairwise selectivity were adversely affected with the production of a Pd\textsuperscript{5+} charge state.

Here the role of SMSI on the pairwise selective addition of parahydrogen to propene over Ir nanoparticles supported on three different metal oxides: TiO\textsubscript{2}, a reducible support that is well-known to induce SMSI, and the non-reducible oxides SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} is examined. For small (c.a. < 1 nm) Ir nanoparticles supported on TiO\textsubscript{2}, we find that SMSI can boost the pairwise selectivity of hydrogenation of propene by a factor of up to 20.
Materials Synthesis and Characterizations

Catalyst Synthesis

Ir/TiO\textsubscript{2} and Ir/Al\textsubscript{2}O\textsubscript{3} with a nominal metal loading of 0.5 weight \% were prepared by a precipitation-deposition method. 1.98 g of TiO\textsubscript{2} support (Alfa Aesar, Catalog No. 43828) or Al\textsubscript{2}O\textsubscript{3} (Catalog No. 43858) was dispersed in 100 mL of deionized water under constant stirring. H\textsubscript{2}IrCl\textsubscript{6}·6H\textsubscript{2}O (0.028 g, Alfa Aesar, Catalog No. 11030) was dissolved in 5 mL deionized H\textsubscript{2}O and mixed with the support solution. Iridium hydroxide was formed by drop-wise addition of a 2.5 mM NaOH solution until the pH value of the solution reached 11. The catalyst dispersion was then aged overnight under continuous stirring, and titrated with a dilute acetic acid solution to pH 7 to ensure precipitation of the hydroxide onto the support. The mixture was filtered, re-dispersed in deionized water, and filtered a second time after stirring overnight. The pre-catalyst was dried at 105 °C overnight, and then calcined (heated in air) at 350 °C for 3 hours to decompose the catalyst precursor.

Ir/TiO\textsubscript{2}-Cl and Ir/SiO\textsubscript{2}-Cl catalysts with nominal metal loadings of 0.5 weight \% were prepared by a modified impregnation method. Using this method, 500 mg of TiO\textsubscript{2} or SiO\textsubscript{2} support was placed in a glass vial where the particles were spread out into a thin layer across the bottom of the vial. Then, 7 mg of H\textsubscript{2}IrCl\textsubscript{6}·6H\textsubscript{2}O was dissolved in 1 mL of DI water and added to the vial until the water level just covered the top of the TiO\textsubscript{2} or SiO\textsubscript{2} support. The vial was then placed under ultrasonication for 30 seconds to provide better mixing before it was placed in the oven at 80 °C to dry slowly. Once the liquid had fully evaporated, the sample was dried at 105 °C overnight, and calcined at 350 °C for 3 hours.
Pre-treatment of Catalysts and Reaction Conditions

Prior to reactions, 10 mg of catalyst was loaded into a U-tube reactor and oxidized in air (50 mL/min) at 400 °C for 1 hr. The reactor was then purged with N₂ at a flow rate of 300 mL/min for 40 minutes, during which the catalyst bed was cooled down to 200 °C and reduced in pure H₂ (50 mL/min) for 1 hr. After reduction at 200 °C, the temperature was decreased to 150 °C followed by purging with N₂ at a flow rate of 300 mL/min for 15 minutes, before the reaction mixture was introduced into the reactor. In all experiments the reactant gas mixture was PE, H₂ and N₂ at flow rates of 20, 120 and 160 mL/min respectively. The species in the reactor effluent was analyzed using NMR (see details for data acquisition below). The sequence of reduction in H₂ (50 mL/min) for 1 hr at one temperature, followed by purging at 150 °C in N₂ (300 mL/min) for 15 minutes, and reaction at 150 °C was repeated for reduction temperatures of 350, 400, 450 and 500 °C, respectively. To test if the results for the Ir/TiO₂ catalyst were consistent with SMSI effects, i.e. that the drop in activity after reduction at 500 °C could be reversed after an oxidation and a low temperature reduction, the catalysts, after the 500 °C reduction, were oxidized in air (50 mL/min) at 400 °C for 1 hr, purged N₂ (300 mL/min), and reduced in pure H₂ (50 mL/min) at 200 °C for 1 hr before being tested again for activity in the reaction at 150 °C.

TEM

High resolution high angle annular dark field STEM images were recorded on a probe aberration-corrected JEM-ARM200cF at 200kV. The following experimental conditions were used: probe size 7 c, CL aperture 30 µm, scan speed 32 µs/pixel, and camera length 8 cm, which corresponds to a probe convergence semi-angle of 11 mrad and collection angles of 76-174.6 mrad. The STEM resolution of the microscope is 0.78
Å. The intensity of atomic columns in STEM HAADF images is proportional to Zn, where Z is the atomic number and n is close to 2, and has a monotonic relationship to sample thickness. Due to the large difference in atomic number, the Ir particles are seen as bright areas against the darker TiO₂ background.

**H₂ and CO Chemisorption**

Chemisorptions using H₂ and CO were performed on the Ir/TiO₂ catalysts after reduction at 200 and 500 °C. Before the measurements, the catalyst was reduced at 200 °C in pure H₂ and then outgassed at the same temperature under inert gas (He at 80 sccm) for 30 minutes before being cooled down to room temperature using a water bath (under the inert flow of gas). The H₂ chemisorption was performed using pure H₂ gas (Airgas, Ultra High Purity). After H₂ titration experiments at room temperature, the sample was outgassed a second time at 200 °C under He for 30 min before CO titration measurements. The CO titrations were also carried out after cooling to room temperature and a 25% CO in He mixture (Airgas, Specialty Gas) was used for these experiments.

**Temperature Programmed Reductions (TPR)**

The temperature programmed reduction was performed using a ChemBET 3000® (Quantachrome Instruments, Inc.) instrument equipped with a thermal conductivity detector. For these experiments, 150 mg of Ir/TiO₂ catalyst (or bare TiO₂ support) was placed in a U-shaped quartz tube. The temperature programmed reduction (TPR) profiles of the catalysts were obtained by recording the hydrogen uptake under flow of 5% H₂ in N₂ as a function of temperature at a 10 °C/min heating rate up to 500 °C.
X-ray Photoelectron Spectroscopy (XPS)

XPS of three Ir/TiO\textsubscript{2} samples which underwent different pre-treatment were recorded on a PHI5000VersaProbell instrument equipped with a hemispherical analyzer operated in Fixed Analyzer Transmission (FAT) mode. A monochromated Al-Ka X-ray source with an energy of 1486.6 eV operating at 47.7W was applied. The Shirley algorithm was implemented to construct the background. C 1s peaked at 284.8 eV was used as the internal standard for shift correction. All three samples were oxidized in air at 50 mL/min for 1 hr, followed by a one-hour reduction in H\textsubscript{2} at 50 mL/min with the catalyst bed at temperatures of 200 and 500 °C respectively. The samples were purged by flowing N\textsubscript{2} at 50 mL/min for 30 mins after oxidation or reduction treatment. To minimize the contact with air before XPS characterization, all samples were stored in air-tight glove box filled with N\textsubscript{2}. The process of transferring catalysts from the catalytic bed to the glove box takes about 2 minutes.

The details of the NMR spectroscopy, calculations of overall conversion and pairwise selectivity were described in the preceding sections.

Results and Discussion

The supported Ir nanoparticle catalysts were synthesized by two different protocols. The deposition-precipitation method using NaOH and an Ir precursor was used to prepare catalysts with low chlorine content on TiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} supports. To investigate the effect of Cl\textsuperscript{-} ions, a modified impregnation method was used in which a chloride containing Ir precursor was impregnated onto TiO\textsubscript{2} and SiO\textsubscript{2} supports (Ir/TiO\textsubscript{2}-Cl and Ir/SiO\textsubscript{2}-Cl). The nominal loading of Ir metal was 0.2 atomic % on all of the supports. The actual Ir loading was quantified for the Ir/TiO\textsubscript{2} catalyst by energy-dispersive x-ray spectroscopy (EDS) and was measured to be 0.2 – 0.3 atom % (Figure
Prior to running hydrogenation reactions, the supported Ir catalysts were oxidized in air at 400 °C and then reduced in pure H₂ at temperatures ranging from 200 to 500 °C.

Figure 6-1. Representative EDS spectrum collected from clusters of Ir/TiO₂. The green bars indicate Ir peak locations. Quantification of the EDS spectra shows 0.2 to 0.3% Ir in atomic percentage (C_{Ti}+C_{Ir}= 100%) for Ir/TiO₂ catalyst, prepared by precipitation-deposition synthesis, oxidized @ 400 °C, reduced in H₂ @ 200 °C. The Ir content measured by EDS was the same (within the experimental uncertainty) for the sample reduced at 200 °C.

Scanning transmission electron microscopy high angle annular dark field (STEM-HAADF) images of the Ir/TiO₂ sample were collected after the freshly synthesized catalyst was reduced at 200 °C (Figure 6-2a,c and Figure 6-3a,c) or 500 °C (Figure 6-2b,d and Figure 6-3b,d). At the higher temperature, the metal nanoparticles appear flattened and in many cases the Ir atoms appears to adopt the lattice of the underlying TiO₂. There are also indications that these particles are somewhat embedded in the TiOₓ support, though it is difficult to draw definite conclusions from the 2D images. The measured particle distributions yielded slightly larger average diameter for the higher temperature reduction (0.7±0.2 vs. 0.5±0.2, see Figure 6-5). No indication of a thin amorphous TiOₓ layer on top of the Ir nanoparticle can be seen in our STEM annular bright field (STEM-ABF) images (Figure 6-6) in which there is neither delocalization
effect nor Fresnel contrast, as in the conventional high resolution TEM images. It is claimed that such a layer can be seen in Figure 1b of Ref.106

Figure 6-2. High resolution STEM-HAADF images at two magnifications of the Ir/TiO$_2$ catalyst (precipitation-deposition synthesis), oxidized at 400 °C, then reduced in H$_2$ at (A, C) 200 °C or 500 °C. Flat shaped Ir particles are indicated by the red arrows. Materials synthesized by Dr. Wei Cheng from University of Florida. Reproduced with permission from ref. 8 © ACS Publications, 2016.

Figure 6-3. High resolution STEM-HAADF images at various magnifications of Ir/TiO$_2$ catalyst, prepared by precipitation-deposition synthesis, oxidized @ 400 °C followed by A, C) H$_2$ reduction @ 200 °C; B, D) H$_2$ reduction @ 500 °C.
Figure 6-4. Bright field TEM images of Ir/TiO$_2$ catalyst, prepared by precipitation-deposition synthesis, oxidized @ 400 °C followed by A) H$_2$ reduction @ 200 °C; B) H$_2$ reduction @ 500 °C.

Figure 6-5. Iridium NP size distribution (counted about 150 to 190 particles for each sample in STEM-HAADF images) of Ir/TiO$_2$ catalyst, prepared by precipitation-deposition synthesis, oxidized @ 400 °C followed H$_2$ reduction @ 200 °C or 500 °C.

Figure 6-6. A high-resolution STEM-HAADF image (left) and corresponding STEM-ABF image (right) of an Ir particle on TiO$_2$. No amorphous layer on Ir particle is visible.

Figure 6-7a, b present the 400 MHz proton NMR spectra of the reactor effluent, acquired in the ALTADENA-PHIP mode (bottom spectra), following reductive pretreatment of the Ir/TiO$_2$ catalyst in pure H$_2$ at 200 °C and 500 °C, respectively. The
hydrogenation products formed at low magnetic field (c.a. 5 mT) were “adiabatically” transported to 9.4 T for NMR detection. At both reduction temperatures, PA exhibits enhanced NMR signals with characteristic ALTADENA intensity pattern. Note the emission phase (downward) peaks of the PA –CH₃ in the ALTEDENA spectra due to the effect of population inversion across the NMR transition. These spectra can be compared to the thermally polarized spectra acquired using n-H₂ rather than p-H₂ in Figure 6-7 (top). The thermally polarized PA signals are proportional to total conversion resulting from pairwise + non-pairwise addition. While the high temperature (500 °C) H₂ pre-treatment decreased the total conversion to PA by a factor of 44, the PHIP signal decreased by only a factor of 2.2. Since the PHIP NMR signal enhancement is the ratio between the PHIP and thermally polarized signals, a 20-fold boost of the PA signal enhancement (and pairwise selectivity) was induced. This is opposite to the trend reported for Pd/TiO₂, where reduction treatment at 500 °C had the effect of decreasing the pairwise selectivity.

Table 6-1. Percent Conversion (Conv) and Pairwise Selectivity (PS) of Ir Nanoparticles on Various Supports

<table>
<thead>
<tr>
<th>Support material</th>
<th>Conversion or Pairwise Selectivity</th>
<th>Reduction Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>200 °C</td>
</tr>
<tr>
<td>TiO₂-Cl</td>
<td>Conv</td>
<td>26.2±1.52</td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>0.4±0.01</td>
</tr>
<tr>
<td></td>
<td>Conv</td>
<td>21.9±1.25</td>
</tr>
<tr>
<td>TiO₂</td>
<td>PS</td>
<td>0.2±0.01</td>
</tr>
<tr>
<td></td>
<td>Conv</td>
<td>20.1±0.57</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>PS</td>
<td>0.2±0.01</td>
</tr>
<tr>
<td>SiO₂-Cl</td>
<td>Conv</td>
<td>19.9±1.60</td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>0.1±0.01</td>
</tr>
</tbody>
</table>

*Re-oxidation and re-reduction.
Figure 6-7. ALTADENA (bottom) and normal (top) $^1$H NMR spectra of products obtained using Ir/TiO$_2$ after reduction in H$_2$ at A) 200 °C, B) 500 °C and C) oxidation in air at 400 °C followed by reduction in H$_2$ at 200 °C. 16 transients were accumulated for all spectra except for the normal spectrum in B (64 transients). Flow rate: 120 mL/min H$_2$; 20 mL/min PE; 160 mL/min N$_2$. The vertical scale is the same for all spectra.

A hallmark of SMSI is the reversibility of the effects. In contrast, changes in the activity and pairwise selectivity due to particle sintering/aggregation are generally irreversible. In the original studies demonstrating SMSI on metal/TiO$_2$ systems, the SMSI were shown to be fully or partially reversible by oxidation treatment followed by mild reduction.$^{34}$ Therefore, we hypothesize that if the observed changes in the pairwise selectivity are truly related to SMSI, they too should be reversible. The spectra in Figure 6-7c were obtained by recycling the catalyst specimen by re-oxidation treatment in air at 400 °C followed by reduction at 200 °C in pure H$_2$. Indeed, both the pairwise selectivity and the overall activity have been restored to nearly the same values as the initial ones (compare Figure 6-7a, c), consistent with SMSI. The pairwise selectivity rose from 0.2% to 3.9% after reduction at 500 °C and then decreased back to 0.5% after re-oxidation.
and then re-reduction at 200 °C, while overall conversion decreased from 21.9% to 0.5% and then increased back to 17.7%. The slightly lower conversion can be attributed to sintering which reduces the surface area of the metal, consistent with slightly larger particle size after the 500 °C reduction. A similar recovery was observed over Ir/TiO₂-Cl (Table 6-1) except for a slight increase of overall conversion, possibly due to loss of Cl⁻ after the oxidation-reduction cycle.¹¹³

Since SMSI can be induced only on a reducible transition metal oxide, control experiments were performed using Ir deposited onto two non-reducible inert supports, SiO₂ and Al₂O₃. The NMR spectra are presented in Figure 6-8 and the results are summarized in Table 6-1. For Ir nanoparticles on these supports, increasing the reduction temperature from 200 to 500 °C resulted in relatively small changes in the pairwise selectivity: 0.2% to 0.8% for Ir/Al₂O₃ and 0.1% to 0.3% for Ir/SiO₂. The total conversion rose from 20.1% to 37.2% over Ir/Al₂O₃ and decreased slightly over Ir/SiO₂. The decrease in conversion over the Ir/SiO₂ could be due to sintering of the Ir particles at the high reduction temperature, although it is also possible that the chloride ions in this sample migrated to the surface during the reductive treatment and blocked some of the active sites. After oxidation and another reduction treatment at 200 °C, some of this chlorine has likely been removed. However, compared to the behavior of the Ir/TiO₂ catalyst, the changes in activity and pairwise selectivity are much smaller and consistent with a non-interacting support. The behavior of the Ir/Al₂O₃ catalyst is different from both the SiO₂ and TiO₂ supported catalysts. The high-temperature reduction significantly increased the conversion, but unlike the Ir/TiO₂ results, the subsequent low-temperature reduction of the Ir/Al₂O₃ catalyst did not reverse the increased activity (within the
The increase in activity with reduction temperature suggests that the IrO\(_x\) on the surface of this catalyst is not reduced at 200 °C.

![Figure 6-8. ALTADENA (A,C,E) and normal (B,D,F) NMR spectra of product gas mixture catalyzed by Ir/TiO\(_2\)/Cl (left), Ir/Al\(_2\)O\(_3\) (middle) and Ir/SiO\(_2\) (right) after reduction in H\(_2\) at 200 °C (A,B), 500 °C (C,D) and oxidation in air at 400 °C followed by reduction in H\(_2\) at 200 °C (E,F). 90° pulse angle was applied for all spectra. 16 transients were accumulated for all spectra. Recycle delays of 2 s and 5 s were applied for ALTEDENA and normal spectra, respectively. Linebroadening of 3 Hz was applied. Gas flow rate: 120 mL/min H\(_2\); 20 mL/min PE; 160 mL/min N\(_2\).](image)

Since the “strength” of SMSI depends on reduction temperature, a series of reduction pretreatments were performed at temperatures ranging from 200 to 500 °C. After each pre-treatment, hydrogenation reactions were performed at 150 °C, a temperature lower than the lowest reduction temperature, to ensure no further SMSI effect is induced during the hydrogenation reaction. After catalyst reduction, NMR spectra of the product gas stream were acquired using a reactant mixture containing propene and 50% para-enriched H\(_2\). Figure 6-9 presents the PHIP signal enhancement, pairwise selectivity, and total conversion as a function of reduction temperature for all of the catalysts. For hydrogenation over the Ir/TiO\(_2\) catalyst, the pairwise selectivity
monotonically increased from 0.2% to 3.9% (a 20-fold increase) upon increasing the reduction temperature from 200 to 500 °C. For Ir/TiO₂-Cl, a sharp rise from 0.5% to 4.4% was observed after reduction at 350 °C, which increased to 5.3% after reduction at 500 °C. Overall conversion (catalytic activity) exhibited the opposite trend, decreasing sharply from 21.9% to 0.5% over Ir/TiO₂ and from 26.2% to 1.9% over Ir/TiO₂-Cl (Figure 6-9B). These results demonstrate that the high temperature H₂-reduction treatment is beneficial for increasing the pairwise selectivity of propene hydrogenation over Ir/TiO₂. The effect on the pairwise selectivity is further enhanced by the presence of chloride.

![Figure 6-9. A) Enhancement and pairwise selectivity as a function of reduction temperature; B) Total conversion vs. reduction temperature. Black solid circles: Ir/TiO₂-Cl. Hollow black circles: Ir/TiO₂. Blue squares: Ir/Al₂O₃. Green triangles: Ir/SiO₂-Cl.](image)

The behavior of the activity with reduction temperature, i.e. the decrease in propene conversion after reduction at 500 °C and recovery of activity with an oxidation and low temperature reduction treatment, is consistent with the expected behavior of SMSI. In an attempt to prove SMSI effects, the catalysts were subjected to H₂ and CO chemisorption analysis after reduction at 200 °C and 500 °C. Due to the very low
metal loading (below 0.5%), the typical decrease in CO adsorption for SMSI effects was not observed. Instead, a small increase in amount of CO adsorbed was measured for the Ir/TiO$_2$ catalyst (from 11 to 17 $\mu$L/g) after reduction at 500 °C, while the H$_2$ chemisorption was too small to be detected. Hydrogen TPR analysis of the Ir/TiO$_2$ catalyst and the TiO$_2$ support without Ir (Figure 6-10A) revealed that the increase in CO adsorption is due to a higher degree of reduction at 500 °C, consistent with previous studies.$^{114}$ The reduction peak at around 135 °C for Ir/TiO$_2$ is most likely due to reduction of IrO$_x$ to Ir metal, while the reduction peaks between 300 and 400 °C are likely due to reduction of IrO$_x$ that interacts strongly with the TiO$_2$ support and/or reduction of TiO$_2$ near Ir particles. The TiO$_2$ support itself is reduced at temperatures in excess of 400 °C.

![Hydrogen TPR](image)

Figure 6-10. Hydrogen TPR of A) bare TiO$_2$ support and Ir/TiO$_2$ catalyst. B) Freshly prepared and recycled Ir/Al$_2$O$_3$. 

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TPR measurements on the Ir/Al$_2$O$_3$ catalyst reveal that at this low Ir loading the IrO$_x$ on the surface of the support is difficult to reduce (Figure 6-10B). Therefore, at a reduction temperature of 200 °C only a small fraction of the IrO$_x$ on the Al$_2$O$_3$ support is reduced, which also explains why no CO adsorption was detected on this catalyst. Higher reduction temperatures are needed to reduce the IrO$_x$ on the Al$_2$O$_3$ support, which explains the increase in conversion with reduction temperature. In contrast to the Ir/TiO$_2$ catalyst, where the effects of the 500 °C reduction were reversible, the Ir/Al$_2$O$_3$ catalyst has been permanently altered by the high-temperature reduction. After oxidation following reduction at 500 °C, the appearance of the TPR curve of the “recycled” Ir/Al$_2$O$_3$ looks very different. Most of the Ir on the surface is now reduced at a lower temperature, consistent with a larger particle size due to sintering after the high-temperature reduction. This was not observed for the Ir/TiO$_2$ catalyst, where all effects were reversible.

The Ir/TiO$_2$ catalyst was analyzed by XPS to probe changes in oxidation state associated with SMSI.$^{32,111,115}$ XPS was performed on three Ir/TiO$_2$ samples following the same pre-treatments as in the PHIP experiments: oxidation at 400 °C only and oxidation at 400 °C followed by reduction at 200 or 500 °C. The Ti 2p and Ir 4f peaks obtained from the Ir/TiO$_2$ catalyst after oxidation at 400 °C, reduction at 200 °C and reduction at 500 °C. Since the Ti 3s peak overlaps the Ir 4f peaks, this region was fitted using one Ti 3s peak and four total Ir 4f peaks, i.e. the Ir 4f$_{7/2}$ and Ir 4f$_{5/2}$ of both IrO$_x$ and Ir metal. Only one Ti 3s peak was used for all peak fits even though the Ti 2p peaks indicated a small contribution from a Ti$^{3+}$ species in addition to the Ti$^{4+}$ of TiO$_2$ (Figure 6-13). Rather than adding a sixth peak, as this would make the peak fitting rather
arbitrary, the contributions from Ti$^{4+}$ and Ti$^{3+}$ to the Ti 3s peak were combined and fitted as one peak. The results from the peak fittings are shown in Figure 6-13. It is evident that even for the catalyst oxidized at 400 °C this region is better fit using both Ir metal and IrO$_x$ peaks. The full width at half maximum for the Ti 3s and Ir 4f peaks was restricted to be between 1.9 and 2.1 eV for consistency between catalysts. Unfortunately, the Ir 4f peaks (the most intense Ir peaks) overlap with the Ti 3s peak of the support. This, together with the very low Ir loading, make it difficult to determine the oxidation state of Ir. Nevertheless, peak fitting using the PHI MultiPak$^{116}$ software suggests that the relative amount of Ir$^0$ increases as reduction temperature increases, in accord with the published in-situ XPS characterization of Ir/TiO$_2$ catalysts with a higher Ir loading$^{108}$ and consistent with the TPR data. Furthermore, the TiO$_2$ support is partially reduced at a reduction temperature of 500 °C. This is evident as a slight broadening of the low energy side of the Ti 2p$_{3/2}$ peak obtained from the Ir/TiO$_2$ catalyst reduced at 500 °C compared to the catalyst reduced at 200 °C (Figure 6-12). The broadening is consistent with reduction of some Ti$^{4+}$ ions to Ti$^{3+}$.$^{117}$
Figure 6.11. Ti 2p and Ir 4f (plus Ti 3s) XPS data obtained from catalysts oxidized at 400 °C, reduced at 200 °C and reduced at 500 °C.

Figure 6.12. Ti 2p$_{3/2}$ XPS data obtained from the Ir/TiO$_2$ catalyst after oxidation at 400 °C followed by reduction at 200 °C (black trace) or 500 °C (blue trace).
In SMSI, the removal of oxygen anions is needed to allow the metal atom and the surface cation to be close enough to allow charge transfer and bonding to occur, and this can promote the migration of TiO$_x$ over the Ir nanoparticle surface or result in a spreading of Ir on the support to maximize Ir-TiO$_x$ interactions (geometrical effect of SMSI). The charge transfer increases the number of metallic and possibly negatively charged Ir atoms at the interface. Based on all of our observations and the literature,
there are several plausible models that can account for the correlation between \( \text{H}_2 \) reduction temperature and pairwise selectivity.

(1) **Geometric.** Loss of hydrogenation activity could be due to a geometric blocking effect resulting from migration of TiO\( _x \) across the metal surface. Even though this layer is not detected by STEM, its existence cannot be unequivocally ruled out because it may not be visible if it consists of only one or two monolayers. In this model, the active metal surface area, and hence the number of metal atoms available to split molecular \( \text{H}_2 \) in non-pairwise addition by the Horiuti-Polanyi (HP) mechanism, would vary as \( \sim r^2 \), where \( r \), the radius of exposed Ir\(^0\) metal, decreases with increasing \( \text{H}_2 \) reduction temperature. If the active sites for pairwise addition are assumed to reside along the Ir-TiO\( _x \) interface on the periphery of the exposed particle surface, the number of such sites would vary as \( \sim r \). Hence, the fractional decrease in active sites for pairwise addition due to migration of TiO\( _x \) would vary as \( \sim 1/r \).

(2) **Electronic.** According to Tauster,\(^{35}\) Ti\(^{3+} \rightarrow \text{Ir} \) charge transfer results in polar-covalent bond formation that can suppress dissociative chemisorption of \( \text{H}_2 \) on the metal, implying a short lifetime on the surface. While this would tend to decrease the total conversion, the weakened adsorbate-surface interaction may favor pairwise transfer involving direct/concerted addition of surface-bound molecular \( \text{H}_2 \) to the substrate via a four membered ring transition state. In this purely electronic SMSI model, geometric blocking is not essential to explain the results.

**Summary**

To summarize, we find that SMSI in the Ir/TiO\( _2 \) system produce a dramatic boost of the PHIP signal enhancement, in contrast to the negative effect of SMSI reported...
recently for Pd/TiO$_2$.\textsuperscript{32} This is brought about by a disproportionate decrease in the non-pairwise addition relative to pairwise addition. The contrasting results for Pd and Ir suggest that the effect of SMSI on pairwise selectivity depends on the specific catalyst system due to different electronic and possibly geometric SMSI effects. A broader survey of other supported metals is necessary to establish a general pattern on the effect of SMSI on pairwise selectivity. Furthermore, Cl$^-$ ions were found to promote pairwise selectivity. Chlorine on the surface is expected to block Ir sites, which could reduce the diffusion of hydrogen on the surface.

Direct addition of molecular H$_2$ to the substrate in a concerted process would preserve the singlet spin order inherent to para-H$_2$. It has been suggested that H$_2$ binds to low coordination metal atoms located at edges or kink atoms on the metal cluster.\textsuperscript{31} The demonstration of a substantial positive effect of SMSI over Ir/TiO$_2$ can be explained if such sites occur at the interface between the metal and oxide support. Alternatively, the weakening of the adsorbate-surface interaction by charge transfer and ionic bond formation could serve this role. Disentangling these effects, and consideration of possible kinetic/diffusion effects on the pairwise selectivity, is an intriguing but challenging subject for future studies.
CHAPTER 7
SURFACE WATERS AQUIRE MAGNETIZED PROTONS

Background

Magnetic Resonance Imaging (MRI) is a non-invasive medical diagnostic tool that produces detailed three-dimensional anatomical images without the use of damaging radiation. MRI uses powerful magnetic fields and radio frequency pulses to excite and detect changes in the direction of the magnetic dipole moments of protons found in the water that makes up living tissues. Remarkably, conventional MRI images rely entirely on the detection of the flipping of proton magnetic nuclei in only one out of every $10^5$ water molecules, which is one reason medical MRI requires lengthy scanning time for patients. Here the discovery of a simple, readily scalable, and inexpensive method for orienting the proton magnetic moments in water molecules, leading to enhancements of the nuclear magnetic resonance transitions by several orders of magnitude compared to normal water is reported. By simply bubbling 50% para-enriched hydrogen gas (hereafter p-H$_2$, the singlet spin isomer of molecular H$_2$) through a volume of liquid water containing an insoluble silica-protected Pt$_3$Sn alloy nanoparticle catalyst, contaminant-free *hyperpolarized* (HP) water can be produced in a matter of seconds. HP methanol and ethanol can also be produced by this approach. In this remarkable phenomenon, where Surface Water Acquire Magnetized Protons (SWAMP), intense stimulated radio wave emission signals are detected in the proton nuclear magnetic resonance (NMR) spectrum. Fast and inexpensive production of HP water could drastically reduce scan times for certain types of MRI. Numerous other applications can also be envisaged.
SWAMP Experiments

Using the NMR tube slurry reactor that was described in detail in our previous report,\textsuperscript{118} low field SIMPLE-PHIP NMR spectra of H\textsubscript{2}O/HOD, CH\textsubscript{3}OH/CH\textsubscript{3}OD and CH\textsubscript{3}CH\textsubscript{2}OH/CH\textsubscript{3}CH\textsubscript{2}OD were acquired following bubbling p-H\textsubscript{2} gas at earth magnetic field (~70 μT). The NMR tube was loaded with 50 mg of insoluble catalyst powder in deuterated water, methanol and ethanol. The solution was de-oxygenated by bubbling N\textsubscript{2} at a flow rate of 50 mL/min for 5 minutes. The head-space of the NMR tube was purged with p-H\textsubscript{2} gas for 2 minutes at a flow rate of 300 mL/min. The NMR tube was then pressurized to 7 bar with p-H\textsubscript{2} and immersed in a hot oil bath at set temperatures for 15 minutes prior to reactions. After bubbling p-H\textsubscript{2} gas through the slurry for 20 s at a flow rate of 350 mL/min, a back pressure was applied to stop the bubbling immediately. The NMR tube was then manually inserted into a 10 mm liquid probe in a 400 MHz magnet as quickly as possible and a single free induction decay was acquired using a 90° pulse. Thermally polarized spectra were acquired using the same procedure except that n-H\textsubscript{2} was bubbled through the fresh solution. Fully relaxed thermally polarized spectra were collected 180 s after insertion of samples. High field experiments at 9.4 T were performed inside the 10 mm liquid probe inside the magnet. The probe was heated to 80 °C by a variable-temperature control system of the NMR spectrometer. Then the procedures that are the same to the low field experiments were performed followed by a 90° pulse. For the near-zero field experiments, the NMR tube was pre-heated to 80 °C in an oil bath for 15 minutes and the oil bath with the NMR tube in it was transferred to a three-layer concentric μ-metal shield manually as quickly as possible, followed by bubbling p-H\textsubscript{2}. The temperature of the oil bath was measured to be 78 °C after bubbling gases. To ensure the reproducivity of the near-zero field
experiment, two consecutive near-zero field experiments were performed immediately before and after an experiment at earth magnetic field (Figure 7-9). For the experiment performed at 3 mT, the solution was positioned at the fringe field of the NMR magnet and the field strength was measured by a Gauss meter.

**Results and Discussion**

**Hyperpolarized Water, Methanol and Ethanol**

![NMR spectra](image)

Figure 7-1. 400 MHz liquid state $^1$H NMR spectra of (A) water-d$_2$ (D$_2$O) (B) methanol-d$_4$ (CD$_3$OD) and (C) ethanol-d$_6$ (CD$_3$CD$_2$OD) obtained using 50 mg Pt$_3$Sn@mSiO$_2$ NPs after bubbling with 7 Bar p-H$_2$ (top spectra) or n-H$_2$ (bottom spectra) at 350 mL/min for 20 s at 120 °C, 105 °C, and 105 °C, respectively. Isotopic impurity protons and protons transferred by proton-deuterium exchange with p-H$_2$ contribute the -OH signals. Proton signals of methyl and methylene groups arise only from isotopic impurities in the per-deuterated solvent. * indicates methanol impurity.

We observed SWAMP NMR signals in a sample prepared by adding 50 mg of an insoluble solid powder of silica-encapsulated (mSiO$_2$) Pt$_3$Sn intermetallic nanoparticles (iNPs) to a 10mm O.D. NMR tube containing about 1.5 mL of per-deuterated water, methanol or ethanol (Cambridge Isotope, DLM-4-25 (D, 99.9%), 99.5% chemical purity). Full details about the Pt$_3$Sn@mSiO$_2$ catalyst are provided in Ref. 118. The NMR tube was fitted with a gas-tight PEEK cap with a 1/16 in O.D. PEEK capillary feed-through to allow bubbling of p-H$_2$ gas through the liquid under pressure.$^{46}$ 50% para-enriched
hydrogen was supplied to the capillary by flowing normal H\textsubscript{2} gas (n-H\textsubscript{2}, 25\% para-enrichment) through a coiled copper tube containing a solid ortho-para interconversion catalyst and immersed in liquid nitrogen.\textsuperscript{119} Once enriched, the p-H\textsubscript{2} is metastable at room temperature in the long-lived, symmetry protected singlet state. Bubbling was controlled by a system of three solenoid valves.\textsuperscript{46}

Three steps were performed leading up to acquisition of the SWAMP NMR spectrum. (1) The NMR tube containing the deuterated water (or methanol or ethanol) and catalyst was pressurized with p-H\textsubscript{2} to 7 Bar and heated in a temperature regulated oil bath (e.g. 120 °C for D\textsubscript{2}O). (2) After purging the headspace of the NMR tube with p-H\textsubscript{2}, the gas was bubbled through the liquid to form a slurry for 20 s in the earth’s magnetic field. (3) When the bubbling stopped, the NMR tube was removed from the oil bath, wiped with a towel to remove oil residue, and quickly inserted into the NMR probe of our 400 MHz Bruker Avance NMR spectrometer. The top spectrum in Figure 7-1A shows the $^1$H NMR spectrum acquired using a $\pi/2$ tip-angle radio-wave pulse immediately after insertion of the sample into the spectrometer. An intense stimulated emission peak of HP DOH dominates the spectrum. The bottom spectrum, which shows only a small absorption peak, was obtained when the same experiment was repeated with normal H\textsubscript{2} (n-H\textsubscript{2}, 25 \% parahydrogen). Similarly, samples of per-deuterated neat d-methanol\textsuperscript{120} and d-ethanol\textsuperscript{121} also exhibited intense proton emission signals, as shown at the top of Figure 7-1B and Figure 7-1C. In d-methanol, both the hydroxyl and methyl protons showed hyperpolarization enhancement, with the hydroxyl protons yielding the strongest enhancement. Figure 1C shows enhanced stimulated emission signals from both the hydroxyl and methylene protons in ethanol, while the methyl proton signal
appears to be unaffected. This spectrum also shows the hyperpolarization of the hydroxyl protons of methanol, a minor contaminant from the prior experiments with d-methanol.

**Effect of Sn**

![TEM images of (A, B) Pt@mSiO₂, (D, E) Pt₃Sn@mSiO₂ and (G, H) PtSn@mSiO₂ at low and high magnification. The lattice spacing of the crystalline lattice is highlighted by the white arrows. Structural models of (C) Pt (111), (F) Pt₃Sn (111) and (K) PtSn (110) surfaces. Three-fold Pt hollow sites are identified by blue triangles. Materials synthesized by Mr. Raghu Maligal-Ganesh from Iowa State University.]

Pt-Sn bimetallic catalysts serve a range of applications,¹²² including reforming and cracking in the petroleum industry,¹²³,⁴²⁻⁴³ selective hydrogenation of C=O versus C=C bonds, as in \( \alpha,\beta \)-unsaturated aldehydes,¹²³ and direct oxidation in methanol fuel cells.¹²⁴ Methanol and other oxygen-containing molecules adsorb preferentially via O-Sn interaction.¹⁴⁻⁴⁶,¹²⁴ To gain insight into the active sites and interactions involved in the
SWAMP effect, we look to the surface studies of water, methanol, and ethanol adsorption on well-defined Pt(111), $\rho(2\times2)\text{Sn-Pt}_3(111)$ and $(\sqrt{3}\times\sqrt{3})_{30^\circ}\text{Sn-Pt}_2(111)$ surface alloys formed under high-vacuum conditions. Temperature-programmed desorption (TPD) mass spectrometry indicates that water and the alcohols adsorb weakly and reversibly on all three surfaces. Alloying Sn into the Pt(111) surface slightly weakens the adsorption. It has been reported that water does not dissociate on Pt-Sn alloys in the absence of an applied potential. The electronic and geometric changes affect the structure of the surface water.

Adsorption and diffusion of hydrogen on Pt and Pt-Sn alloys has been extensively studied both computationally and experimentally. Facile dissociative adsorption of $\text{H}_2$ occurs at three-fold Pt(111) sites. As illustrated in Figure 7-2C, F and K, the Pt(111) surface consists of contiguous three-fold Pt sites, while the Pt$_3$Sn(111) surface bears only isolated three-fold Pt sites. Pt$_2$Sn(111) (not shown) and PtSn(110) surfaces are devoid of the three-fold sites. The hydrogen adsorption energy on Pt(111) is insensitive to the adsorption site, with $<$4 kJ/mol variation among atop-Pt, hcp-PtPtPt, bridge-PtPt and fcc-PtPtPt sites. These same sites in Pt$_3$Sn(111) also have similarly small differences in energy, while the atop-Sn site is highly unfavorable (-79 kJ/mol). With a barrier of only 5 kJ/mol, diffusion of hydrogen on Pt(111) is very rapid (at our experimental temperatures), while on $(2\times2)$ Pt$_3$Sn(111), the diffusion barrier of 41 kJ/mol is significantly higher. Unfavorable interactions with tin have the effect of blocking H ad-atom diffusion. This lack of hydrogen mobility has profound implications for the kinetics of hydrogenation reactions on the surface. We believe that this suppression of diffusion is vital to the SWAMP effect.
The SWAMP catalyst, Pt₃Sn@mSiO₂, was synthesized by a novel ship-in-a-bottle approach.⁴⁶,⁵¹ Encapsulation in the mSiO₂ sheath allows the ordered intermetallic structure to be obtained by high-temperature annealing while protecting against particle aggregation and sintering.⁴⁶,⁵¹ Pt@mSiO₂ and PtSn@mSiO₂ nanoparticle catalysts were similarly synthesized and tested for SWAMP activity (see below). Transmission Electron Microscopy (TEM) images of all three particle types are presented in Figure 7-2A-H. The core-shell structures are clearly evident: metal cores are seen as dark spots, while the silica shell appears as the outer layer in a lighter shade of grey. The Pt₃Sn@mSiO₂ (~17 nm metal core) and PtSn@mSiO₂ (~21 nm metal core) catalysts were synthesized by incorporation of Sn into the Pt@mSiO₂ particles with a ~14 nm metal core, resulting in particle size increases. The lattice spacing of the crystalline planes, as revealed by the HRTEM images (Figure 7-2B, E and H), matches the known values for the corresponding intermetallic alloys.¹¹⁸

The availability of Pt@mSiO₂, Pt₃Sn@mSiO₂ and PtSn@mSiO₂ iNP catalysts that mimic the model surfaces with three-fold Pt sites that are contiguous, isolated, or absent, provided us the opportunity to systematically investigate the dependence of SWAMP on these surface structures. While Pt₃Sn@mSiO₂ was found to produce intense SWAMP NMR signals in water, methanol and ethanol, no discernable signal enhancement was observed using Pt@mSiO₂ or PtSn@mSiO₂ (Figure 7-3), suggesting the importance of isolated three-fold Pt sites in the SWAMP activity. Isolated three-fold Pt sites are known to dissociate H₂ with a low activation barrier,⁴⁷,⁴⁹-⁵⁰ while Sn sites restrict H ad-atom diffusion, thereby protecting the incipient singlet-state spin order of parahydrogen against statistical randomization.
Our data provide clues and constraints on the SWAMP mechanism:

(1) For methanol and ethanol, the highest NMR signal enhancement is observed on the hydroxyl proton (Figure 7-1).

(2) Net emission is observed for -OH groups in water, methanol and ethanol.

(3) Net emission peaks are also observed for the non-exchangeable CH₂ and CH₃ protons of ethanol and methanol, respectively. In the first bubbling experiments, these signals have similar intensity as the -OH peak. Subsequently, the thermal -OH peak grows-in disproportionally compared to the other peaks.

(4) The hydroxyl peaks in the fully relaxed, thermally polarized spectra of methanol (Figure 7-4A) and ethanol (Figure 7-4B) recorded before and after bubbling of p-H₂ exhibit intensity increases of 30% and 415%, respectively. The larger increase for ethanol resulted from multiple bubbling cycles. This is evidence of proton-deuteron exchange between hydrogen molecules and
deuterated hydroxyls of the alcohols. Moreover, the observation of a
dissolved HD triplet, with 1:1:1 intensity ratio and 42.9 Hz J-coupling
constant,\textsuperscript{129-131} as seen in the expanded views in Figure 7-4, further confirms
hydrogen-deuterium exchange. The HD triplet was also observed in methanol
solutions containing dissolved pyridine (Figure 7-5). The deuterons in HD can
only originate from methanol-d\textsubscript{4} molecules.

(5) The initial deuteration levels of the d-water is 99.9\%. If polarization transfer
does not occur by hydrogen-deuterium exchange, then it would have to be
mediated by intermolecular dipolar interactions (SPINOE\textsuperscript{132} effect) at only 1
out of every 1000 water adsorption sites. In this case, the SWAMP signal
would depend on the level of protonation of D\textsubscript{2}O. In contrast, a hydrogen-
deuterium exchange signal is expected to be independent of the protonation
level, consistent with the data.

(6) Aprotic solution (e.g. pyridine-N\textsuperscript{15} dissolved in deuterated water and
methanol) did not exhibit any SWAMP enhancement.
Table 7-1. Substrates do not exhibit SWAMP effect.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Catalogue Number</th>
<th>Purity</th>
<th>%D</th>
<th>%15N</th>
<th>Concentration</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-(-)+)-Glucose</td>
<td>Sigma G8270</td>
<td>≥ 99.5%</td>
<td>0</td>
<td>N/A</td>
<td>100 mM</td>
<td>D₂O</td>
</tr>
<tr>
<td></td>
<td>Sigma-Aldrich G8898</td>
<td>≥ 99%</td>
<td>0</td>
<td>N/A</td>
<td>100 mM</td>
<td>D₂O</td>
</tr>
<tr>
<td>Glycine</td>
<td>Aldrich 233315</td>
<td>≥ 99%</td>
<td>≥ 99.9%</td>
<td>N/A</td>
<td>pure</td>
<td>N/A</td>
</tr>
<tr>
<td>Acetic Acid-d₄</td>
<td>Cambridge Isotope, NLM-305-0.5</td>
<td>≥ 99%</td>
<td>&gt;98%</td>
<td>&gt;98%</td>
<td>100 mM</td>
<td>CD₃OD</td>
</tr>
<tr>
<td>Pyridine (¹⁵N)</td>
<td>Cambridge Isotope, NLM-305-0.5</td>
<td>98%</td>
<td>0</td>
<td>&gt;98%</td>
<td>100 mM</td>
<td>D₂O</td>
</tr>
<tr>
<td>Pyridine (¹⁵N)</td>
<td>Cambridge Isotope, NLM-305-0.5</td>
<td>98%</td>
<td>0</td>
<td>&gt;98%</td>
<td>100 mM</td>
<td>CD₃OD</td>
</tr>
</tbody>
</table>

Figure 7-4. Fully relaxed thermally polarized ¹H NMR spectra of (A) methanol-d₄ and (B) ethanol-d₆ before (bottom) and after (top) bubbling p-H₂ over Pt₅Sn@mSiO₂ at 105 °C. Note that only the -OH hydrogen signal increases after H₂ bubbling, while the peaks of the non-exchangeable methyl and methylene signals, which arises from the isotopic impurities, are unchanged by the bubbling.
The net reactions for D\textsubscript{2}O and the alcohols can be written (not including the isotopic impurities):

\[ \text{p-H}_2 + D\textsubscript{2}O \xrightarrow{\text{Pt}_3\text{Sn}} DOH + DH \]  
\[ (7-1) \]

\[ \text{p-H}_2 + CD\textsubscript{3}OD \xrightarrow{\text{Pt}_3\text{Sn}} CD\textsubscript{3}OH + DH \]  
\[ (7-2) \]

\[ \text{p-H}_2 + CD\textsubscript{3}CD\textsubscript{2}OD \xrightarrow{\text{Pt}_3\text{Sn}} CD\textsubscript{3}CD\textsubscript{2}OH + DH \]  
\[ (7-3) \]

The detailed hydrogen-deuterium exchange mechanism is still under investigation. A lower-limit on the SWAMP NMR signal enhancement can be estimated from the ratio of the SWAMP NMR peak integral to the difference in the peak integrals of the fully-relaxed \textsuperscript{1}H spectra recorded before and after H\textsubscript{2} bubbling. Signal enhancement factors, before correction for relaxation losses, of 2.0 and 3.7 were obtained for the -OH proton in DOH and CD\textsubscript{3}OH, respectively. Interestingly, a 1:1 D\textsubscript{2}O/d-methanol mixture yielded a signal enhancement of 8.9. The net emission signals of the non-exchangeable methyl and methylene hydrogens can be accounted for in the strong spin-spin coupling regime in the low magnetic field, either by J-couplings in the isotropic phase\textsuperscript{97, 136} or possibly by through-space dipole-dipole interactions in the...
surface-adsorbed state. That these signals are comparable in magnitude to the -OH peak signal for the first bubbling experiment is convincing statistical evidence that the -OH group is hyperpolarized via a hydrogen-deuterium exchange mediated mechanism.

Figure 7-6. $^1$H NMR spectra of (A) pure methanol (B) methanol with pyridine and (C) water with pyridine obtained using 50 mg PtSn@mSiO$_2$ NPs after bubbling p-H$_2$ at 350 mL/min for 20 s at different temperatures. Note that the top spectrum in (C) was obtained after bubbling p-H$_2$ at 120 °C instead of 105 °C. The dotted lines highlight the chemical shift of dissolved H$_2$.

Figure 7-7. $^1$H NMR spectra of a mixture of methanol and water at a volume ratio of 1 using 50 mg PtSn@mSiO$_2$ NPs after bubbling p-H$_2$ at 350 mL/min for 20 s at different temperatures.
Effect of Magnetic Field

Figure 7-8. $^1$H NMR spectra of methanol using 50 mg Pt$_3$Sn@mSiO$_2$ after bubbling p-H$_2$ at 350 mL/min for 20 s at different magnetic field. A 90° pulse was applied to acquire each spectrum.

Figure 7-9. $^1$H NMR spectra of methanol using 50 mg Pt$_3$Sn@mSiO$_2$ after bubbling p-H$_2$ at 350 mL/min for 20 s at 0, 50 and 0 μT consecutively.

To gain further insight into the SWAMP spin dynamics, bubbling was carried out at a series of four different magnetic fields: near-zero field, earth’s field ($\approx$ 70 μT), the
fringe of the NMR magnet (3 mT) and high field (9.4 T). Figure 7-8 shows that intense SWAMP NMR signals were observed only at ~70 μT and 3 mT, and not near-zero field or 9.4 T. The absence of a SWAMP effect at near zero field indicates the importance of symmetry breaking Zeeman interactions. On the other hand, the absence of a SWAMP effect at high field implies the importance of strongly coupled spins.

The observation of parahydrogen enhanced NMR signals via a single hydrogen atom transfer is highly unusual. Indeed, pairwise addition (i.e. where both H atoms of the same H₂ molecule are chemically incorporated into an unsaturated substrate) is stated as a fundamental pre-requisite to observe parahydrogen enhanced NMR. In the PASADENA¹³⁷-¹³⁸ and ALTADENA⁴¹ effects, pairwise addition occurs by hydrogenation of an unsaturated substrate molecule. Adducts that have been hyperpolarized via hydrogenation chemistry include acetate,¹³⁹-¹⁴⁰ pyruvate,¹⁴¹ lactate,¹⁴²-¹⁴³ hydroxyethyl propionate,¹³⁶ succinate,⁹,¹⁵ choline¹⁴⁴-¹⁴⁵ and hydrocarbons.⁵ However, the requirement for pairwise addition can also be fulfilled by a chemical intermediate but not necessarily to the net reaction. In spin-transfer catalysis, parahydrogen and an exchangeable ligand are reversibly bound within the same intramolecular J-coupled network of an octahedral Ir complex. During the lifetime of this complex, coherence transfer of parahydrogen spin order to the nuclei of the ligand occurs before it dissociates. Therefore, the fundamental requirement of pairwise addition is not obviated.¹⁴⁶ Exchangeable ligands (typically an N-heterocyclic organic compound) that have been demonstrated to be hyperpolarizable by this so-called SABRE effect include pyridine,¹⁴⁶ nicotinamide,¹⁴ nicotinic acid,¹⁴⁷ N₂-diazirine,¹⁴⁸ methanol¹⁴⁹ and acetylene.¹⁵⁰ Parahydrogen enhanced NMR can also be observed by a Pairwise Replacement (PR)
of two non-polarized protons of a surface-bound substrate with the two protons originating as a singlet proton pair. One hydrogen parahydrogen induced polarization (oneH-PHIP) is a rather rare phenomenon in which single hydrogen polarization is observable when the two protons of the H\textsubscript{2} molecule form a strongly coupled system on the catalytic intermediate followed by chemical transfer of only one of the protons to the ligand. The oneH-PHIP was implicated in the hydroformylation catalysis on Pt and Ir carbonyl complexes in solution, where net emission of the CHO proton was observed at high magnetic field. Net emission or net absorption NMR peaks were observed, depending on the relative signs of the isotropic chemical shift difference and J-coupling.

The SWAMP observations are consistent with a mechanism involving similar quantum mechanics. At low magnetic fields, the H ad-atom pair is a strongly coupled spin system. Most likely, one of the hydrogen ad-atoms remains bound to the three-fold Pt site, while the other loses its electron to the metal and becomes incorporated into the adsorbed water network, thereby breaking their chemical and hence magnetic equivalence. Through space dipolar couplings to other protons, Pt or Sn could also break magnetic equivalence. An H atom exchanges with a hydroxyl deuterium of D\textsubscript{2}O (or CD\textsubscript{3}OD or CD\textsubscript{3}D\textsubscript{2}OD) adsorbed onto an adjacent Sn site. The hyperpolarized DOH* molecule desorbs from the surface into the bulk liquid phase. A detailed mechanism of the surface spin dynamics is under development.

**Summary**

Hyperpolarized liquid water can be produced by at least one other technique: dynamic nuclear polarization (DNP) technique. DNP is a promising approach for preparing hyperpolarized substrates for localized angiography, protein-ligand interactions, and brain perfusion studies. However, DNP requires highly complex
and expensive instrumentation, and suffers from low throughput. By comparison, SWAMP offers simplicity, low cost, scalability, and speed for producing hyperpolarized water and ethanol, molecules with obvious biological relevance. Using the insoluble Pt$_3$Sn@mSiO$_2$ SWAMP catalyst, hyperpolarized water was produced in a matter of seconds. As we have shown in previous studies using the mSiO$_2$-encapsulated Pt-Sn nanoparticles, the hyperpolarized liquid is produced without contamination by dissolved radical polarizing agents or transition metals complexes. SWAMP is the only method that can rapidly produce hyperpolarized liquid water. This should accelerate FDA approval, which, together with the low-cost and simplicity of the SWAMP method, could result in its widespread deployment.

Through the advanced ship-in-a-bottle synthesis, the surface chemistry of mesoporous Pt-Sn intermetallic nanoparticles have been tuned by changing the Pt:Sn ratio, leading us to the discovery of the SWAMP effect. Three-fold Pt surface sites, not isolated Pt atoms, appear to be crucial for splitting H$_2$ and hindering diffusion of the H ad-atoms, thereby preserving the singlet-spin order in the dissociated form of the molecule for a time that is long enough to allow symmetry breaking interactions and proton exchange to occur. Systematic studies of the field-dependence of the SWAMP effect, combined with DFT calculations of the adsorbate surface geometries and spin dynamics simulations, could lead to an even more precise understanding of this remarkable phenomenon. While the observed enhancement factors are several orders of magnitude lower than the theoretical maximum, we hasten to add that all the signal enhancements will automatically increase by a factor of 3 if 99% enrichment is used rather than 50% p-H$_2$. Moreover, at the common clinical MRI magnetic field of 1.5 T, the
signal enhancement would further increase by at least a factor of \(~6\) relative to the value at 9.4 T. Nevertheless, heterogeneous SWAMP catalysis is a promising approach for inexpensive, high-throughput production of contamination-free hyperpolarized substrates with potential magnetic resonance imaging applications. The tunability of the surface chemistry of intermetallic NPs has opened the door to exciting new possibilities for applying heterogeneous catalysts in the preparation of hyperpolarized small molecules as well as the fundamental understanding of surface chemistry.
CHAPTER 8
CONCLUSIONS AND OUTLOOKS

Since its theoretical prediction in 1986 and experimental demonstration a year later, PHIP has been continuously evolving into a powerful tool to provide mechanistic insights of homogeneous catalytic processes.²⁻³ Twenty years later, PHIP via heterogeneous catalytic processes represents another milestone in the field.⁵ Thereafter, one more tool is added into the toolbox of characterization of both homogeneous and heterogeneous catalysts.

Besides the fundamental significance in catalysis chemistry, it sees growing promises that PHIP may one day becomes a viable tool for clinical diagnosis by MRI and MRS, thanks to the dramatic signal enhancement afforded by the technique and its utter simplicity. The scope of organic substrates that can be hyperpolarized by PHIP has been expanding drastically in the past decade. A milestone from this aspect is the discovery of SABRE, which does not require an unsaturated substrate and chemical modification of the substrate.

Efforts toward the development of PHIP can be divided into two categories based on the chemistry involved, hydrogenation and exchange chemistry. Each category has its advantages and limitations. Hydrogenation by heterogeneous catalysis has the advantages of easy separation from product mixture, catalyst recovery, regeneration and compatibility with continuous-flow production of hyperpolarized molecules in high throughput. The limitations are the relatively low polarization level, arising from the low pairwise selectivity. The pairwise addition of a dihydrogen molecule to an organic substrate on the surface of a heterogeneous catalyst is not immediately perceivable because of the fast diffusion of the chemisorbed protons. The seemingly fundamental
difficulty delayed the discovery of PHIP by heterogeneous catalysis by two decades after the initial discovery of PHIP. Nonetheless, the polarization level has been improved significantly from below 1% on metal oxide-supported metal nanoparticles to 11.6% on Pt-Sn intermetallic nanoparticles, albeit at the expense of total yield of the HP product. Decreasing the nanoparticle size from the tens of nanometers to a few nanometers while maintaining the intermetallic phase will enhance the yield per catalyst mass while maintaining the high pairwise selectivity. With the advance of nanomaterials’ synthesis, undoubtfully, the polarization level will continue increasing in the foreseen future. The intermetallic nanoparticle catalyst is particularly promising as various combinations of metals tailored for different reactions have been demonstrated, yet only Pt-Sn intermetallic nanoparticles were explored for PHIP effect. It represents a big unexplored territory.

A fundamental question yet to be addressed is the mechanism of pairwise addition. Two catalytic processes can be proposed. In one process, an intermediate state of four-member ring is formed on the surface and leads to the adduct, without breaking the hydrogen bond before reaction. In the other process, the two protons dissociate and add to the substrate in a stepwise fashion. The pairwise addition is facilitated by a high diffusion barrier. By a survey of the published work from other groups and our group, an anti-correlation between the pairwise selectivity and total conversion is widely observed in different catalytic systems. Theoretical calculations, for instance, Density Function Theory may shed light on the mechanisms and guide the design of catalyst optimized for pairwise addition.
Long-lived singlet state of hyperpolarized dimethyl maleate was produced over Pt$_3$Sn@mSiO$_2$ nanoparticles in methanol. However, no conversion of dimethyl acetylene dicarboxylate to dimethyl maleate in aqueous phase was observed from the initial attempt. The aqueous phase is vital for biomedical applications. Although hyperpolarized hydroxyl ethyl propionate was produced in aqueous phase, the enhancement factor is low. A high-pressure and high-temperature reactor may enhance the conversion and PHIP signal enhancement in aqueous phase, although construction of such a reactor is not trivial.

The observation of hyperpolarized water via the SWAMP effect is a remarkable discovery and could potentially broaden the applications of water-related magnetic resonance in various research fields, as discussed in Chapter 7. Certainly, there are limitations associated with the SWAMP method and possible strategies to tackle these limitations are discussed here. First, the SWAMP effect was observed exclusively in deuterated solvent, largely due to the suppression of thermally polarized background $^1$H signal by deuteration at high magnetic field. To observe the SWAMP effect in non-deuterated solutions, low-field in situ NMR spectroscopy in the $\mu$T to mT regime can be performed since the hyperpolarized signal, once produced, is almost independent of the detecting magnetic field strength while the thermally polarized is drastically reduced at such a low field. Our preliminary field-dependent studies clearly demonstrated the SWAMP effect in the $\mu$T to mT regime. Therefore, the implication of applying SWAMP effect for low-field MRI is immediate. Second, the NMR enhancement factor of the SWAMP effect is relatively low. The understanding of the correlation between the surface composition of the Pt-Sn NPs, temperature, pressure, magnetic field strength
where the SWAMP effect is induced and the symmetry breaking of p-H$_2$ and the exchange rate on the Pt-Sn surface is fundamentally interesting and significant. Certainly, it calls for thorough and systematic future investigations which in turn facilitate the optimization of materials, reaction conditions and magnetic field strength tailored for the SWAMP effect. Third, a sampling robot that can precisely control the transport time of the hyperpolarized water from where the reaction takes place to the NMR magnet for detection will facilitate the quantitative analysis of the signal enhancement factors of the SWAMP effect.
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(119) The copper tube was packed with 30 mesh iron(iii) oxide hydroxide (Sigma Aldrich, catalog), an efficient ortho-para interconversion catalyst.

(120) d-methanol, Cambridge Isotopes, DLM-24-10 (D, 998.%), 99.5% chemical purity.

(121) d-ethanol, Sigma Aldrich, 186414-5G (D>99.5%), 99.9% chemical purity.


BIOGRAPHICAL SKETCH

Evan Wenbo Zhao was born in Baoding City of Hebei Province, China in 1988. He obtained his Bachelor of Engineering (First Class Honor) in the School of Materials Science and Engineering at Nanyang Technological University in Singapore in 2012. He came to University of Florida at the same year to pursue a Ph.D. in physical chemistry as a graduate school fellow. He spent his first two years studying plasmonic nanomaterials with Prof. Wei David Wei. In 2014, he joined Prof. Clifford R. Bowers' group to work on the project of parahydrogen induced polarization by heterogeneous catalysis. His research interest is at the interface of nanomaterials related to heterogeneous catalysis and NMR spectroscopy in gas, liquid and solid state. His career plan is to advance the application of NMR spectroscopy for fundamental understanding of nanomaterials.