Template Effect and Ligand Substitution Methods for the Synthesis of Iron Catalysts: A Two Part Experiment for Inorganic Chemistry

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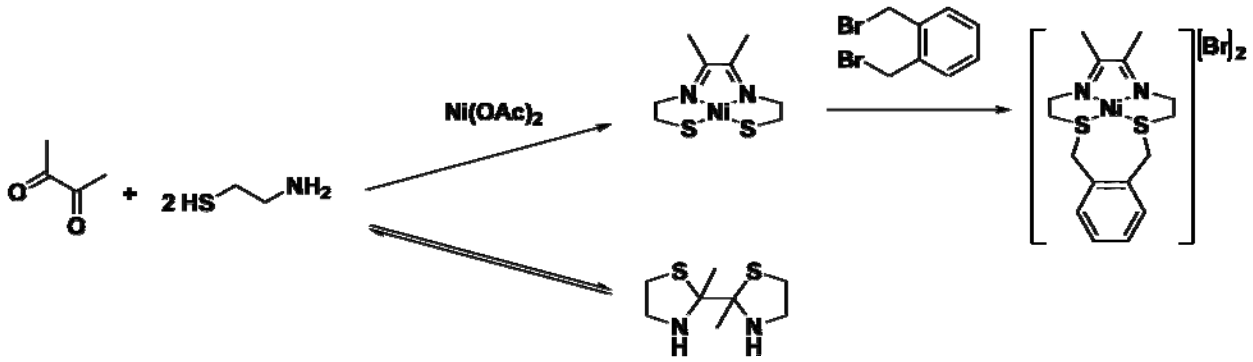
Laboratory Notes for Students

Part 1 - Synthesis of a Tetradentate P-N-N-P Iron Complex using the Template Effect and its Isolation using Salt Metathesis

Introduction

The synthesis of multidentate ligands for transition metal complexes is often a long and tedious process requiring a series of organic transformations using simpler, commercially available ligand precursors. In many cases standard techniques utilized in organic syntheses cannot be used to make a particular ligand because of competing or undesirable side-reactions (e.g. polymerizations). By contrast, it has been shown that transition metals may be used to arrange the starting materials so that they assemble directly on the metal centre itself into the desired ligand, thereby solving both of the problems mentioned previously. This pre-organization of ligand precursors on a metal ion for the generation of a desired product is called the **Template Effect**. In the absence of the metal centre, the same ligand precursors often combine to make different products.

Scheme S1. Synthesis of Tetradentate Nickel Complexes using the Template Effect.



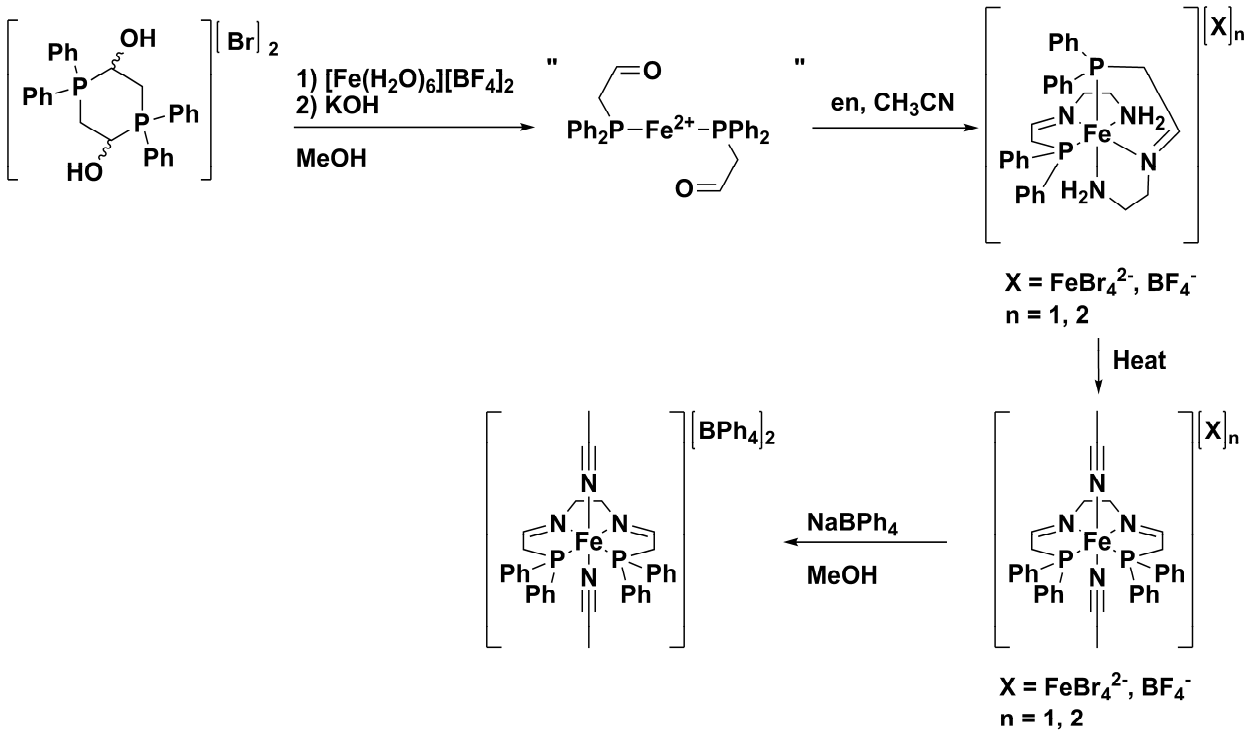
An example of the template effect is illustrated in the synthesis of tetradentate nickel complexes (**Scheme S-1**).[1,2] In the absence of the Ni^{2+} ion, the ligand starting materials, 2-aminoethanethiol and butane-2,3-dione, react to generate 2,2'-dimethyl-2,2'-bithiazolidine.[1] If the metal centre is present, on the other hand, a nickel complex with a tetradentate ligand is formed. Moreover, the tetradentate nickel complex reacts with 1,2-bis(bromomethyl)benzene to produce a tetradentate macrocyclic ligand.[2] Attempts to synthesize macrocyclic ligands without a metal template are notoriously difficult and often yield small amounts of desired product because the reactions are not selective. Typically polymers and rings of various sizes are produced.[3]

Another concept that is useful in inorganic chemistry is **Salt Metathesis**: the exchange of ions between two different species.[4, 5] Essentially, when two ionic salts are dissolved in a solvent and then mixed, the cations and anions can trade partners to form new compounds.[4, 5] If one of those salts is insoluble then it will precipitate from solution, and drive the metathesis reaction to completion. This is especially useful when purifying compounds because a desired product can be isolated by filtration, thereby leaving the impurities in solution. In general, it is difficult to predict whether or not a specific ion pair will be insoluble but, as a good rule of thumb, ions with similar sizes are better matched and will have lower solubilities[6] due to the higher lattice energies resulting from improved crystal packing.[4, 5]

In this experiment you will investigate the synthesis of a metal complex with a tetra-dentate ligand using the **Template Effect**.[7] The ligand has two phosphorus donors as well as

two nitrogen donors, and the metal template is the Fe^{2+} ion. The iron starting material will be mixed with a phosphonium salt (IUPAC name: 2,5–dihydroxy–1,1,4,4–tetraphenyl–1,4–di–phosphonio-cyclohexane dibromide) and base to generate a phosphine aldehyde *in situ* bound to the metal centre (**Scheme S2**).[7] Then, ethylenediamine (en) will be added. It will react with the aldehyde in a Schiff base reaction using the metal centre as a template. An intermediate species containing two tridentate ligands is generated initially as a kinetic product but, with heating, a complex with a tetradentate ligand will finally form. This is the thermodynamic product.[7] The iron complex will be dissolved in a solution containing a mixture of counter ions. Therefore, a

Scheme S2. Synthesis of a Tetradentate Iron Complex using the Template Effect and Salt Metathesis.

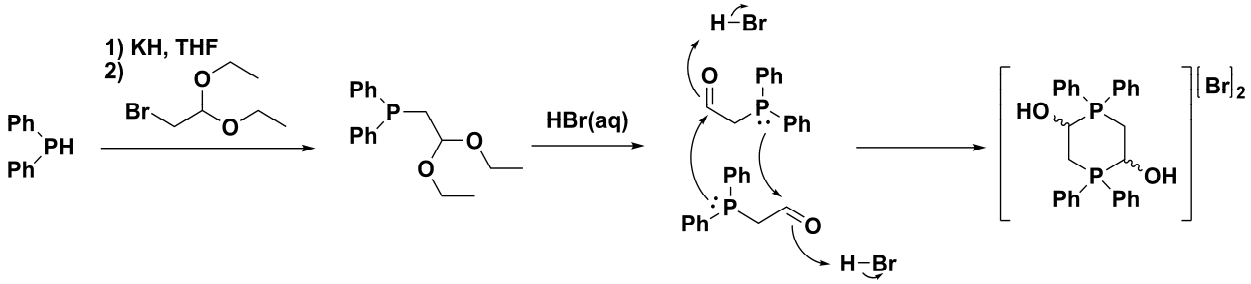


salt metathesis reaction will be performed using sodium tetraphenylborate to isolate a pure product (IUPAC name: bis(acetonitrile)(N,N'-bis(2-(diphenylphosphino)ethylidene)ethane-1,2-diamino)iron(II) tetraphenylborate).[7]

The phosphonium salt that you will use is not commercially available (phosphonium refers to a phosphorus atom that is positively charged, similar to an ammonium cation). It is

synthesized in a private laboratory and will be given to you for the purpose of this experiment. The phosphonium salt is actually a dimer of two phosphine aldehydes and is synthesized using an S_N2 reaction (**Scheme S3**).[7] A simple phosphine, diphenylphosphine, is deprotonated using a strong base to generate a very strong nucleophile. This is then used to displace the bromide of bromo-acetaldehyde diethyl acetal to produce a phosphine compound with a protected aldehyde

Scheme S3. Synthesis of the Phosphonium Salt Starting Material.



functionality.[7] Addition of a strong acid deprotects the aldehyde, but the resulting product is unstable.[7] The lone pair on phosphorus can attack the aldehyde, and in the presence of excess acid this is trapped as an alcohol.[7] Two of the deprotected phosphine species selectively react to produce a very stable six-membered ring.[7]

The dimeric phosphonium salt has many advantages that make it an ideal starting material and much easier to use than traditional phosphorus-containing ligand precursors. Phosphines are routinely used in transition metal chemistry but they are often poisonous, air-sensitive (some will ignite upon exposure to air) and extremely smelly oils. By contrast, the phosphonium dimer you will use is a "masked" phosphine. It is an air- and moisture-stable, odourless solid that can be easily weighed and stored. Whenever the phosphine component is required, it can be "unmasked" in the reaction mixture using strong base.[7]

In this experiment you will also encounter a new type of NMR spectroscopy: ^{31}P NMR. Phosphine ligands are very popular in inorganic chemistry not only because they are good σ donors but also because the phosphorus-31 nucleus is NMR active. It is 100% abundant and has a spin of ½, just like hydrogen and carbon-13.[8] Much information can be revealed from the ^{31}P NMR spectrum of a compound, such as the number of inequivalent phosphorus nuclei, and whether or not the phosphorus nuclei are close to any neighbouring NMR active nuclei

(phosphorus-phosphorus as well as phosphorus-hydrogen coupling may occur in a manner similar to that observed for two inequivalent hydrogen nuclei in a ^{1}H NMR but usually with a larger coupling constant).[8] In addition, the chemical shift of a phosphorus signal is indicative of its chemical environment and oxidation state; (1) Shifts seen below 0 ppm are typical of free phosphines with three P–C or P–H bonds; (2) shifts seen between 10 and 40 ppm are typical of phosphonium salts with four P–C bonds, and (3) chemical shifts seen above 50 ppm are typical of phosphines with three P–C bonds coordinated to a metal centre.[8]

Part 2 - Ligand Substitution of a Tetradentate P-N-N-P Iron Complex using an Analogue of Carbon Monoxide to Synthesize a Catalyst Mimic

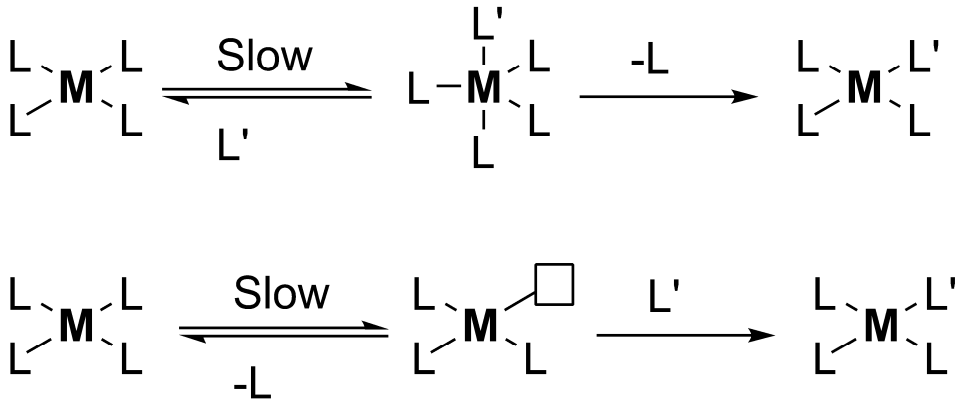
Introduction

The exchange of ligands on a transition metal complex is referred to as a ligand substitution reaction, which can occur through an associative or a dissociative mechanism.[9-12] There are some intermediate cases, but they often lie closer to one of the extremes than the other, and are thus called either associative-like or dissociative-like.[12] As the name suggests, an associative mechanism involves attack of a new ligand on a metal centre, and then release of one of the original ligands (**Scheme S4**).[9-12] Associative mechanisms are sped up by a high concentration of the new ligand, as well as by less bulky ligands on the original complex, because the rate limiting step is the attack of the new ligand on the metal centre.[9-12] By contrast, a dissociative mechanism involves loss of one of the original ligands first, followed by coordination of the incoming ligand (**Scheme S4**).[9-12] Dissociative mechanisms are favoured by large, sterically demanding ligands that "push off" other ligands, and by ligands with a high *trans* influence, because the rate determining step is the loss of the initial ligand.[9, 12]

One of the earliest known and frequently used ligands in organometallic chemistry is the carbonyl or CO ligand, which is also found in the active sites of many naturally occurring enzymes. A carbonyl ligand is a relatively weak σ donor, but energetically it has a low lying anti-bonding orbital that can interact with a filled d-orbital on a metal centre.[9, 10] Electron density from the d-orbital can be donated by the metal into the anti-bonding orbital of CO in a process called **back donation**, which strengthens the metal carbonyl bond, but weakens the C≡O triple

bond (thus carbonyl ligands are called π acidic or acceptor ligands, **Scheme S5**).[9, 10] This

Scheme S4. Associative (Upper) and Dissociative (Lower) Mechanisms for Ligand Substitution.[9]

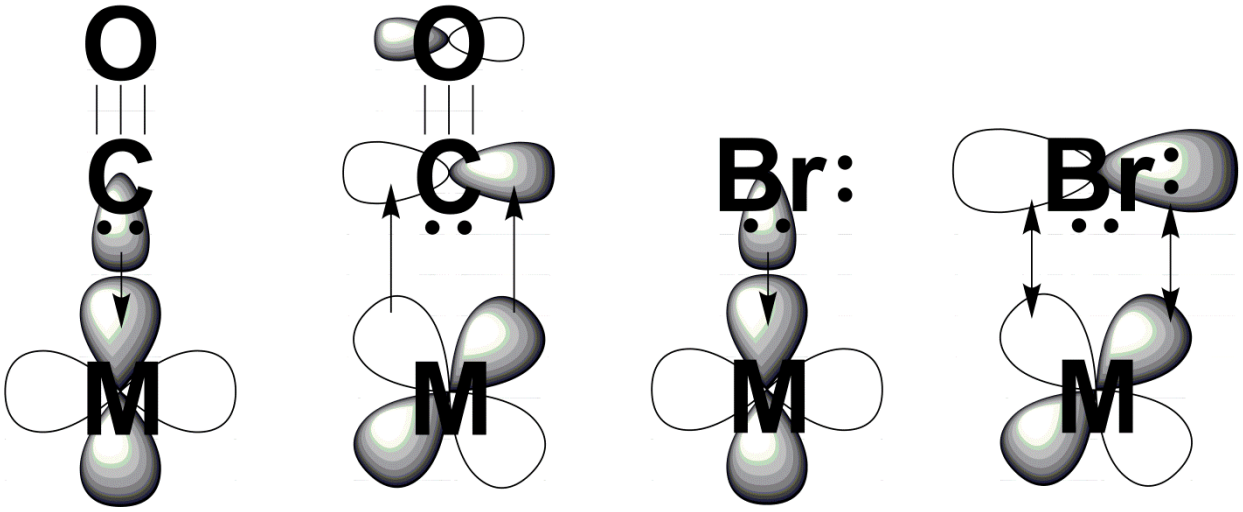


weakening of the C≡O triple bond is reflected in the infrared spectrum of carbonyl complexes. As the bond is weakened the frequency of the C≡O bond stretch is decreased.[9, 10] Moreover, the more electron rich the metal centre, the more electron density it has to donate to the carbonyl ligand and, thus, the frequency of the C≡O stretch is driven to lower values. The wavenumbers of C≡O stretches for metal carbonyl complexes are usually observed in the range between 1750 and 2100 cm^{-1}, whereas that of free C≡O has a value of 2143 cm^{-1}.[9, 10]

By contrast, ligands with lone pairs, such as a bromide ligand, have the opposite effect. The electrons in the filled d-orbitals on the metal centre and the lone pair electrons on the ligand repel each other and weaken the metal-ligand bond (thus ligands with lone pairs are called π donors, **Scheme S5**).[11] Furthermore, the more electron rich the metal centre, the more electron density there is in the d-orbitals, and therefore the stronger the repulsion with the ligand lone pairs. If the metal has empty d-orbitals, however, then the lone pairs on the ligand donate into the empty orbitals and form a metal-ligand π bond, which strengthens ligand binding.[11]

Catalysis is at the heart of inorganic chemistry, but economic and political pressure for more sustainable, environmentally friendly practices has provided a driving force for the development of greener catalysts which incorporate cheap, abundant metals.[13] Asymmetric transfer

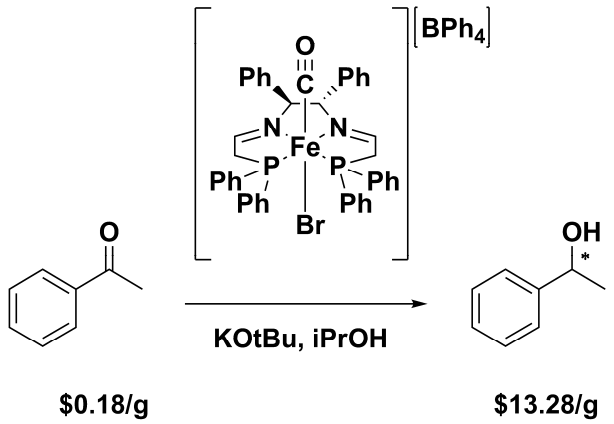
Scheme S5. Orbital Interactions for a Carbonyl versus a Bromide Ligand.



hydrogenation is an area of research that has been extensively studied, but despite all the work done in this field almost all of the catalysts developed to date employ expensive, as well as toxic, platinum group metals.[14] Recently, however, highly active iron asymmetric transfer hydrogenation catalysts containing chiral tetradentate and CO ligands have been reported (**Scheme S6**).[15, 16] The asymmetric transfer hydrogenation of prochiral ketones is an important process because it is used by the pharmaceutical, perfume, and food industries in the synthesis of expensive consumer products.

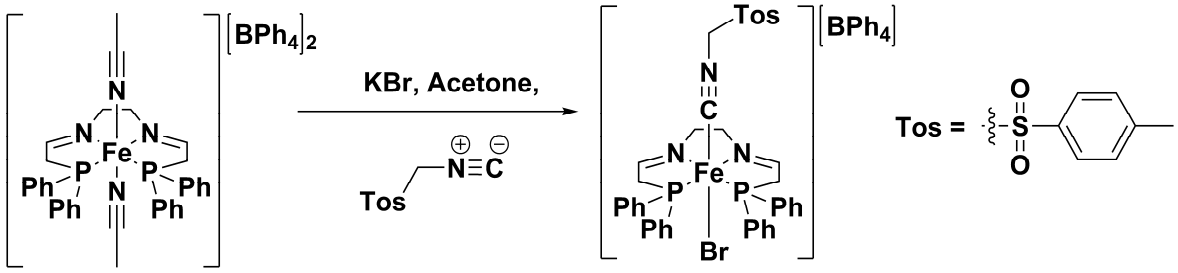
In this portion of the experiment you will perform a ligand substitution reaction with the tetradentate iron complex synthesized previously. The iron starting material will be dissolved in acetone with an excess of KBr as well as one equivalent of *p*-toluenesulfonylmethyl isocyanide and gently heated. An isocyanide binds to metals much like CO in that it is a relatively weak σ donor, but a strong π acceptor. In addition, the isocyanide is a solid that can be easily stored and weighed. It is also significantly less dangerous than CO gas. Both the isocyanide and bromide ligands will replace the original acetonitrile ligands and bind to the metal centre *trans* to each other (**Scheme S7**). This is an extremely favourable arrangement because the π donor is opposite a π acid. The complex that will be synthesized today (IUPAC name: bromocarbonyl-

Scheme S6. Tetradentate Iron Complex used for the Asymmetric Transfer Hydrogenation of Ketones.[14]



(N,N'-bis(2-(diphenylphosphino)ethyl-idene)ethane-1,2-diamino)iron(II) tetraphenylborate) is very similar to the asymmetric transfer hydrogenation catalysts discussed previously, except that the tetradentate ligand is achiral, and the carbonyl ligand has been replaced by an isocyanide.

Scheme S7. Synthesis of the *p*-Toluenesulfonylmethylisocyanide Iron Complex.



Safety Notes:

Acetone (CAS No. 67-64-1): Acetone is an extremely flammable liquid. It is not normally considered dangerous, but the normal precautions should be employed. ORL-RAT LD50: 5800 mg/kg.

Acetonitrile (CAS No. 75-05-8): Acetonitrile is harmful if swallowed, inhaled or absorbed through the skin. Overexposure has caused reproductive disorders in laboratory animals. May cause skin irritation. Lachrymator - avoid breathing vapour. ORL-RAT LD50: 2730 mg/kg.

Diethyl Ether (CAS No. 60-29-7): Diethyl ether is an extremely flammable solvent. Exposure to moisture tends to form peroxides, which may be explosive. The solvent is a potent narcotic. ORL-MAN LDLo: 260 mg/kg. ORL-RAT LD50: 1215 mg/kg.

Ethylenediamine (CAS No. 107-15-3): This compound is harmful if swallowed, inhaled or absorbed through the skin. ORL-RAT LD50: 500 mg/kg. It has an irritating ammonia odour (vapour pressure is 10 mm at 20^{o}C), so it should only be used in the **fumehood**.

Iron(II) tetrafluoroborate hexahydrate (CAS No. 13877-16-2): $Fe(BF_4)_2 \cdot 6H_2O$ FW 337.55 This compound is highly corrosive and a severe irritant. Harmful if swallowed, inhaled or absorbed through the skin. Causes severe skin burns and eye damage. Hygroscopic. Store in a desiccator.

Methanol (CAS No. 67-56-1): Methanol may be fatal if swallowed. It is harmful if inhaled or absorbed through the skin. It is a flammable liquid. ORL-HMN LDLo: 143 mg/kg. ORL-RAT LD50: 5628 mg/kg.

Potassium bromide (CAS No. 7758-02-3): This compound is not normally considered harmful, but the normal precautions should be taken.

Potassium hydroxide (CAS No. 1310-58-3): This compound is highly corrosive and very hygroscopic. Ingestion will produce violent pain in the throat. ORL-RAT-LD50: 1.23 g/kg. If contacted with the skin, wash with large quantities of water.

Sodium tetraphenylborate (CAS No. 143-66-8): $C_{24}H_{20}BNa$; Mol wt 342.24 Freely soluble in water, acetone and methanol. This compound is extremely toxic if ingested. May be harmful if inhaled or absorbed through skin. May cause eye, skin and respiratory tract irritation. ORL-RAT-LD50: 288 mg/kg. If contacted with the skin, wash with large quantities of water.

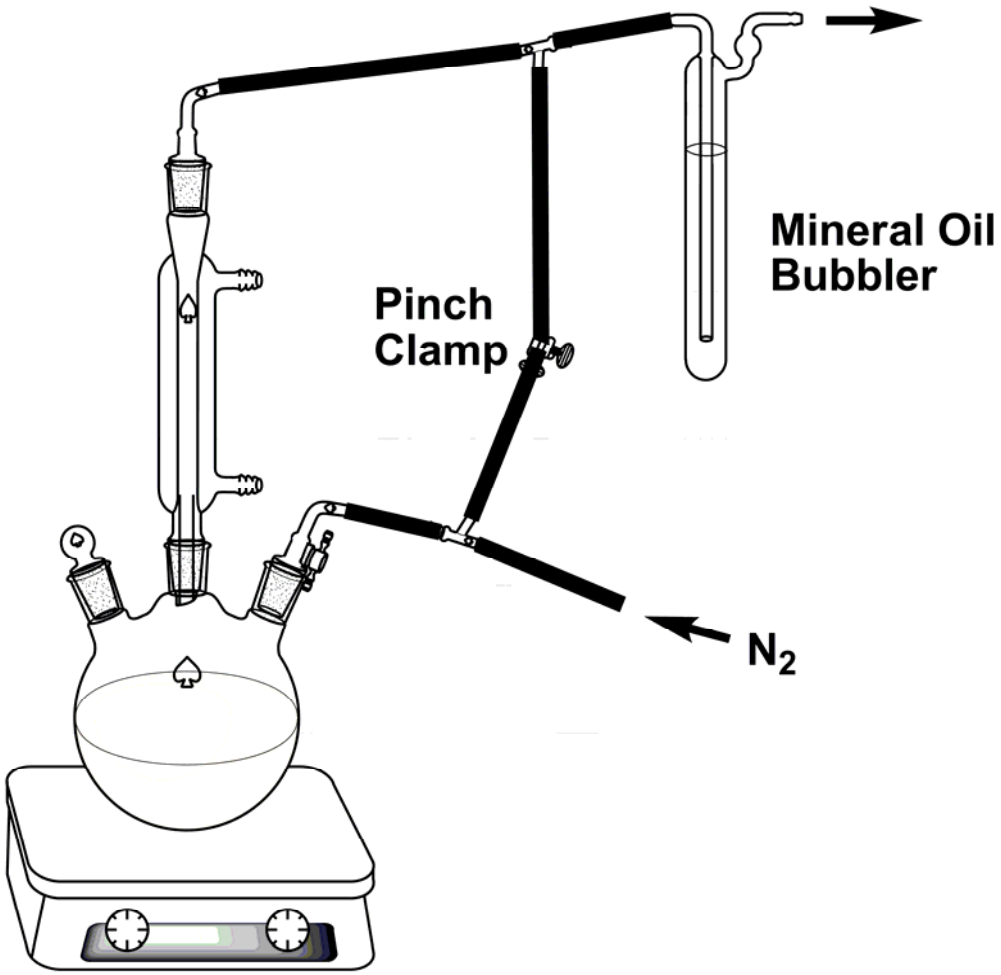
p-Toluenesulfonylmethyl isocyanide (CAS No. 36635-61-7): (tosylmethyl isocyanide) Linear formula $CH_3C_6H_4SO_2CH_2NC$; Mol wt. 195.24 This compound is toxic by ingestion. Avoid direct inhalation or contact with skin. Wear proper protective equipment and take normal precautions. The compound and its solutions MUST be stored in a refrigerator set at about 2^{o} C.

Hexanes (CAS No. 110-54-3): Hazardous in case of skin contact (permeator), of ingestion, and of inhalation. Slightly hazardous in case of skin contact (irritant), and of eye contact (irritant).

The substance may be toxic to peripheral nervous system, skin, central nervous system (CNS). Hexanes is an extremely flammable solvent.

Nitrogen (CAS No. 7727-37-9): Nitrogen is nontoxic, but may cause suffocation by displacing the oxygen in air. Lack of sufficient oxygen can cause serious injury or death.

Figure S1. Experimental Apparatus including the Nitrogen Gas Bypass Lines.



The Experimental Apparatus

The apparatus to be used in these syntheses consists of a 100 mL, 3–neck, round–bottom flask equipped with a Teflon-coated, magnetic stir bar, as illustrated in **Figure S1**. The three

necks of the flask are fitted with: (a) a ground-glass stopper in the left, (b) a condenser in the middle and (c) a gas-inlet adapter in the right. The top of the condenser is also fitted with a gas-inlet adapter. Attached to the two gas-inlet adapters is a system of Tygon (or red-rubber) tubing which includes two "T" (or "Y") glass joints and a pinch-clamp located on the "bypass" portion. The tubing finally terminates in a gas-bubbler assembly.

Part 1: Preparation of bis(acetonitrile)(N,N'-bis(2-(diphenylphosphino)ethylidene)ethane-1,2-diamino)iron(II) tetraphenylborate

Carefully flush the apparatus under a medium flow of N_2 to remove any trace O_2 and H_2O vapours before adding any of the reagents. Open the pinch-clamp on the by-pass tubing and then close the stop-cock on the right-neck of the flask (**in that order!**) to maintain a positive N_2 gas pressure over the top of the condenser.

Remove the glass stopper and insert a powder funnel in the left-neck of the 100 mL flask. **Being sure to leave a small gap in the neck of the funnel during the addition to allow N_2 gas to escape**, carefully transfer 0.16 g of the phosphonium dimer and 0.13 g of $[Fe(H_2O)_6][BF_4]_2$ to the flask. Using a glass pipette, add 6 mL of methanol to the flask through the powder funnel. Remove the powder funnel and plug the neck with a ground glass stopper. Maintaining a positive pressure of N_2 gas over the mixture, stir the contents of the flask for about 5 minutes to dissolve the two solids in the methanol.

Under a medium flow of N_2 gas, unstopper the flask and re-insert the powder funnel. Using a glass pipette, add 2 mL of 0.26M KOH in methanol (or alternatively add a solution of 0.030 g of KOH in 2 mL methanol). The solution will initially turn dark green, but then rapidly becomes pale yellow. Restopper the flask and stir for 2 minutes under a positive pressure of N_2 gas. Unstopper the flask again, re-insert the powder funnel and, using a glass pipette, add 1 mL acetonitrile. Restopper the flask and stir for an additional 3 minutes under a positive pressure of N_2 gas. Unstopper the flask once more, re-insert the powder funnel again and, using a glass pipette, add 1 mL of 0.25 M ethylenediamine in acetonitrile (or alternatively add a solution of 0.015 g ethylenediamine in 1 mL acetonitrile). The solution will rapidly turn a dark wine-red colour.

Maintaining a positive pressure of N_2 gas over the solution, heat the solution to 50°C using a water bath. Continue to heat until the solution turns a reddish-orange colour (45 minutes to 1 hour). Remove the water bath and cool the solution to room temperature under a positive pressure of N_2 gas. Turn off the gas flow and remove the N_2 gas apparatus.

Unstopper the flask and re-insert the powder funnel. Using a glass pipette, add a solution of 0.20 g $NaB(C_6H_5)_4$ in 5 mL methanol dropwise over 5 minutes with stirring. The solution should turn cloudy and pink, with a large amount of precipitate. Stir for approximately 5 minutes, and then collect the pink precipitate under vacuum using a sintered glass crucible. Wash the collected product with two 5 mL portions of methanol, as well as two 5 mL portions of diethyl ether. Dry under vacuum for 15 minutes, weigh and store in a desiccator.

Part 2: Synthesis of bromocarbonyl(N,N'-bis(2-(diphenylphosphino)ethyl-idene)ethane-1,2-diamino)iron(II) tetraphenylborate

Reassemble the apparatus used in Part A (**Figure S1**) Carefully flush the apparatus under a medium flow of N_2 to remove any trace O_2 and H_2O vapours before adding any of the reagents. Open the pinch-clamp on the by-pass tubing and then close the stop-cock on the right-neck of the flask (**in that order!**) to maintain a positive N_2 gas pressure over the top of the condenser.

Transfer 0.15 g of the iron complex produced in Part A to a 50 mL beaker and add 4 mL of acetone. The resulting clear solution should have an orange-red colour. Under a medium flow of N_2 gas, remove the stopper and insert a powder funnel into the left-neck of the 100 mL round bottom flask. Using a glass pipette, add the orange-red solution to the 100 mL flask. Restopper the left neck of the flask and, under a positive pressure of N_2 gas, stir the solution for 5 minutes. Unstopper the flask and re-insert the powder funnel. **Being sure to leave a small gap in the neck of the funnel during the addition to allow N_2 gas to escape**, add 0.2 g of KBr, followed by the dropwise addition of 5 mL of 0.025M p-toluenesulfonyl-methyl isocyanide in acetone (or alternatively add a solution of 0.024 g p-toluenesulfonylmethyl isocyanide in 5 mL acetone).

Restopper the flask and, under a positive pressure of N_2 gas, heat the flask to 40°C using a water bath. Continue to heat for 20 to 30 minutes (until solution turns yellow usually accompanied by the formation of a large amount of precipitate). Under a positive pressure of N_2 gas, cool the solution to room temperature. Stop the N_2 gas flow and remove the N_2 gas apparatus.

Add 25 mL hexanes (or alternatively pentane) and collect the yellow precipitate under vacuum using a sintered glass crucible. Wash the collected product with two portions of 10 mL distilled water, two portions of 10 mL methanol, and two portions of 10 mL diethyl ether. Dry under vacuum for 15 minutes, weigh and store in a desiccator.

Take the infrared spectrum of your product as a Nujol mull and compare it with that of the product run as a KBr disc (Figure S6), paying particular attention to the ν(C≡N) region of the vibrational spectrum. [17]

Part 1 Exercises

Figures S2, S3 and S4 show the ^{31}P spectra of (a) diphenylphosphine (b) the phosphonium dimer and (c) the tetradentate iron(II) complex, respectively. Note that only Figure S2 displays a proton-coupled phosphorus pattern. The others are proton-decoupled spectra. Refer to these figures in answering the following questions.

(1) For diphenylphosphine, explain the origin of the splitting pattern (doublet of quintets) observed for the single phosphorus nucleus.

(2) Structurally, the phosphonium dimer adopts a chair conformation similar to that of cyclohexane. Taking stereochemistry into account, draw all the possible chair conformations.

(3) Using your answer to (2) as a guide, account for the origin of the two observed peaks in the ^{31}P NMR spectrum of the pure compound. Is the synthesis of the phosphonium dimer a stereospecific reaction?

(4) Tabulate the chemical shifts of the phosphorus signals for the three compounds (you may use an average value for diphenylphosphine). Note the trend in these values and account for it in terms of the chemical environment around the phosphorus centres.

Part 2 Exercises

Figures S5 and S6 show the ^{31}P NMR and the infrared spectrum of the final product, respectively. Figure S7 displays the infrared spectrum of the free p-toluenesulfonylmethyl isocyanide. Refer to these figures in answering the following exercises.

(5) Account for the shift in the wavenumber of the C≡N bond stretch of the final complex compared with that of the free ligand. Would you expect the bromide ligand to play a role in affecting this value? If so, in what manner?

(6) Compare the chemical shift of the phosphorus centres in the products of parts (A) and (B). Explain the similar values keeping in mind the following factors: (a) charge on the complex ion and (b) π acceptor abilities of the trans ligands (note: acetonitrile is generally considered to be a good σ donor but a very poor π acceptor).

(7) Taking into account the oxidation state of the metal and the number of ligands coordinated to it, calculate the total electron count on the iron centre for the products of both parts of this experiment.

(8) Using your answer to (7) as a guide, would you expect the ligand substitution reactions to proceed through an associative or dissociative mechanism? Explain your reasoning.

Figure S2. The ^{31}P NMR spectrum of diphenylphosphine in CD_2Cl_2 at 121 MHz.

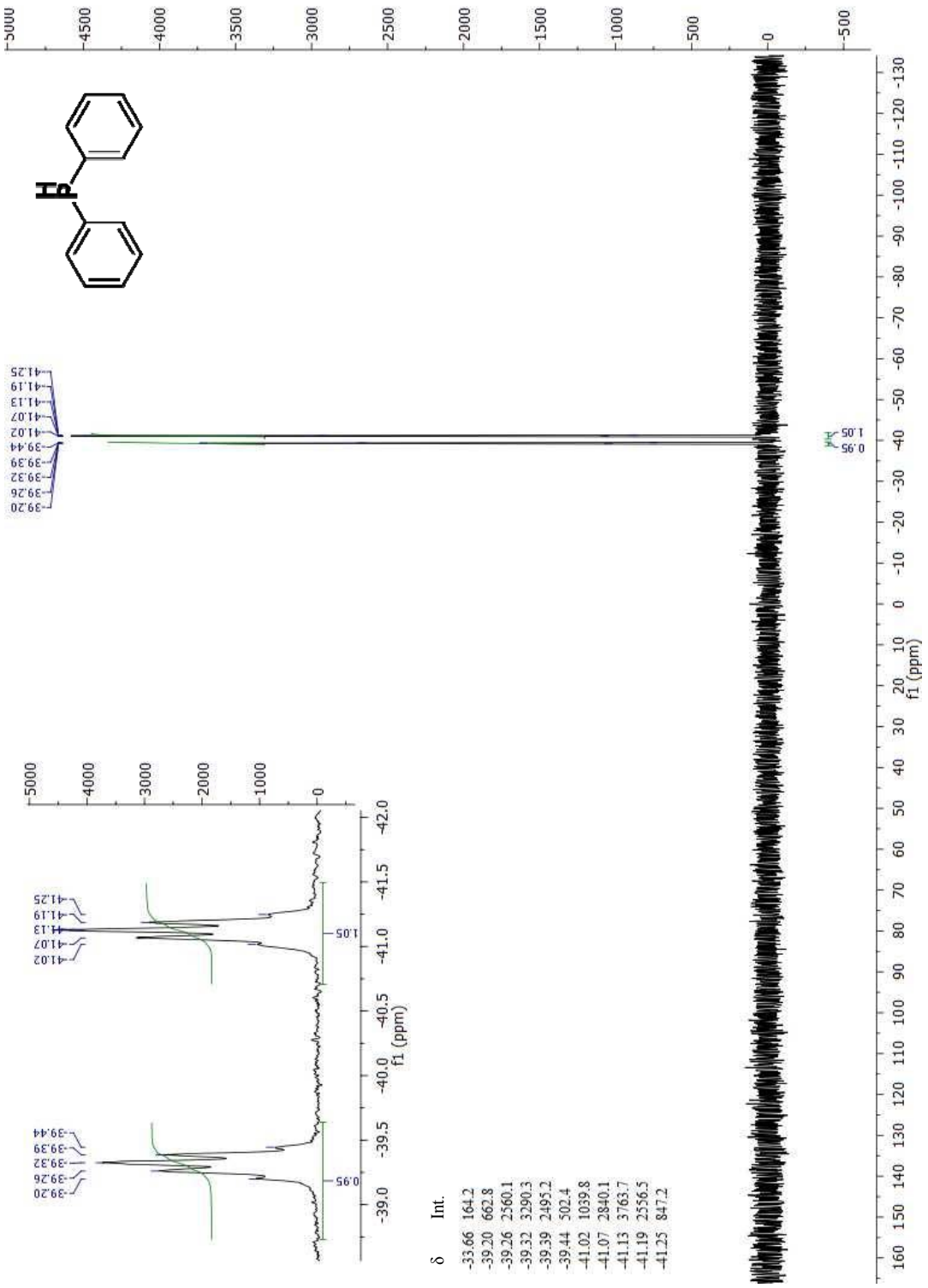


Figure S3. The ^{31}P {^{1}H} NMR spectrum of the phosphonium dimer in CD_2Cl_2 at 162 MHz.

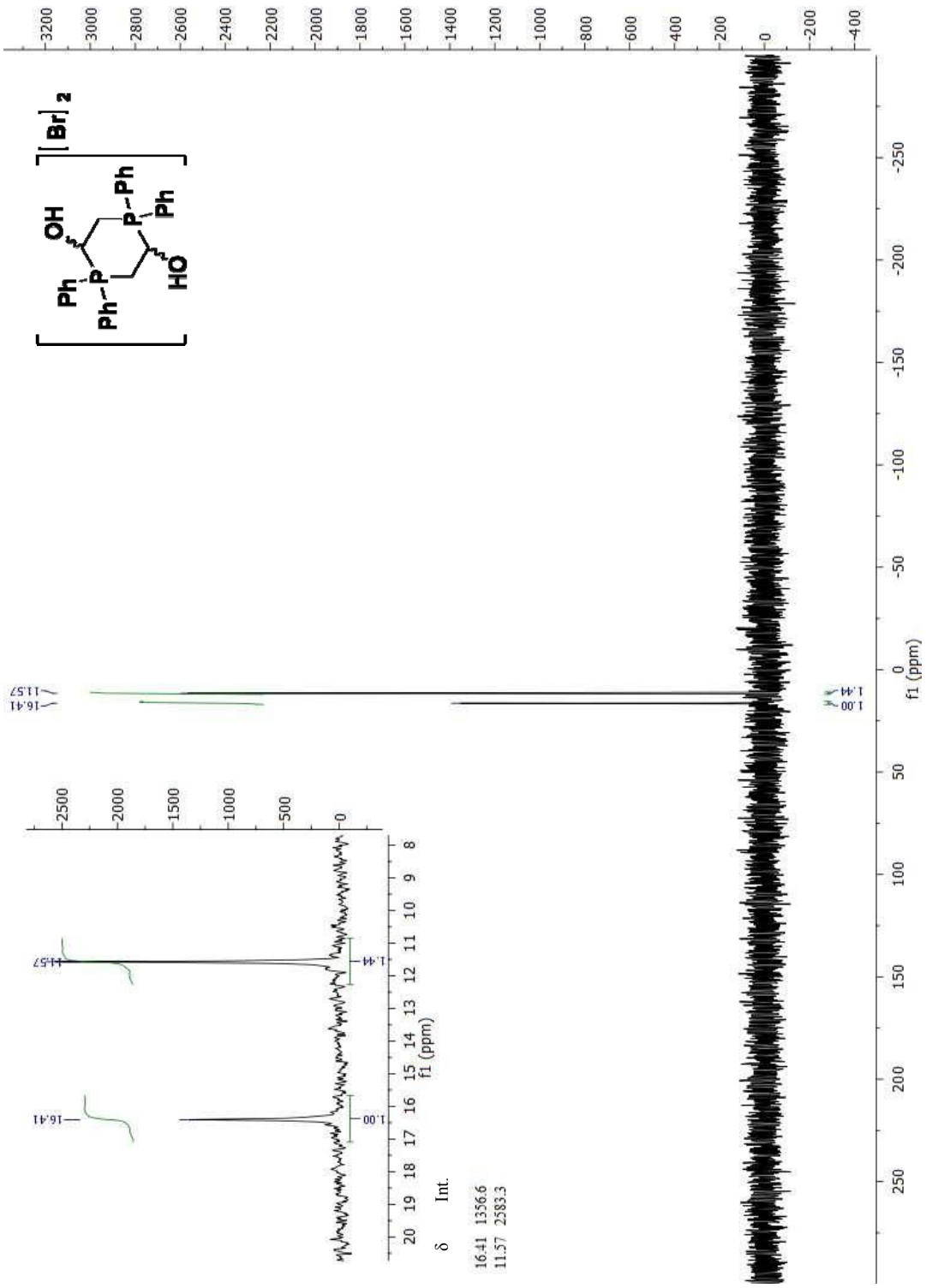


Figure S4. The ^{31}P {^{1}H} NMR spectrum of the tetradentate iron complex in CD_3CN at 162 MHz.

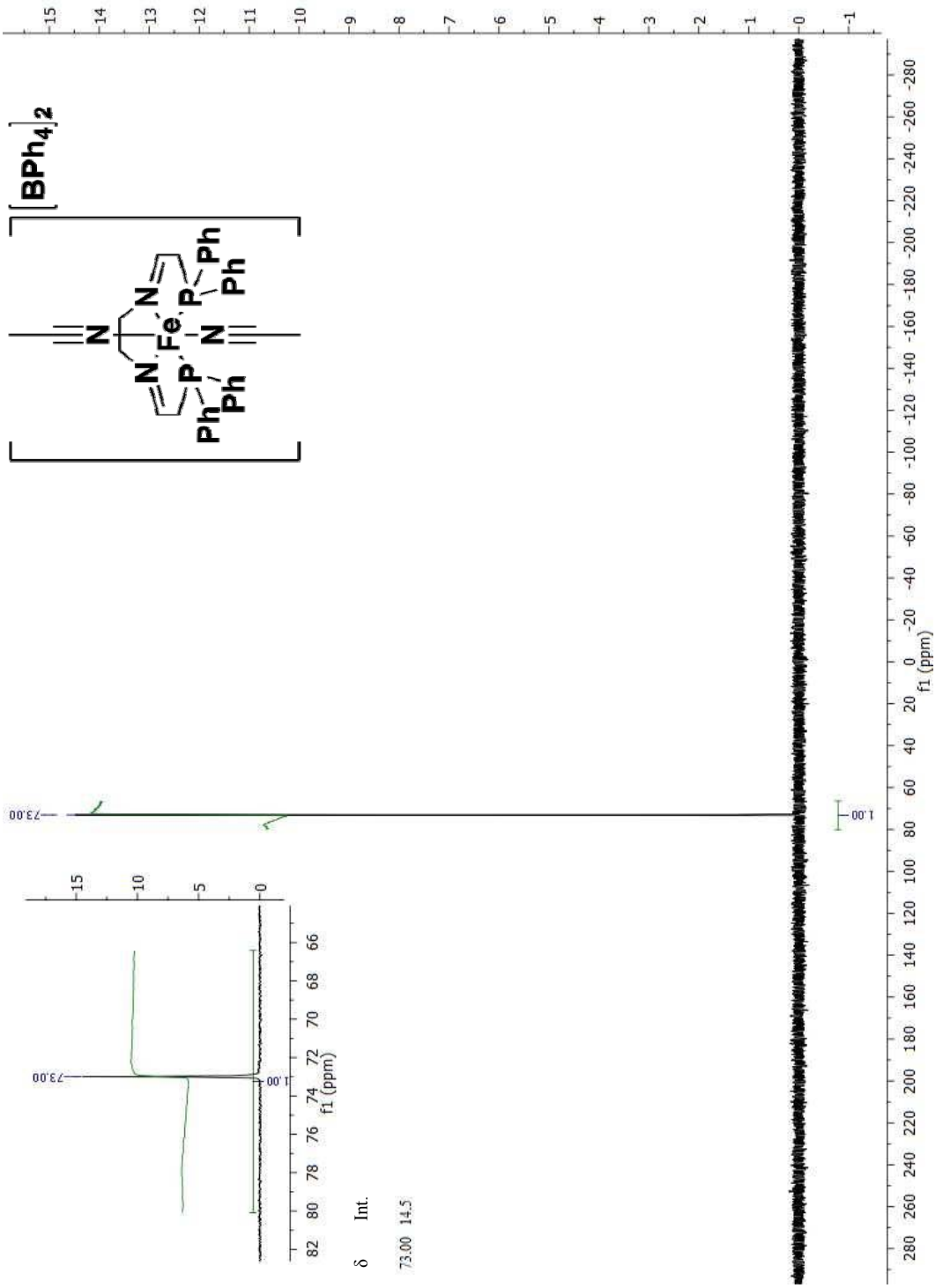


Figure S5. The ^{31}P {^{1}H} NMR spectrum of the tetradentate PNNP, isocyanide iron complex in $(CD_3)_2SO$ at 162 MHz

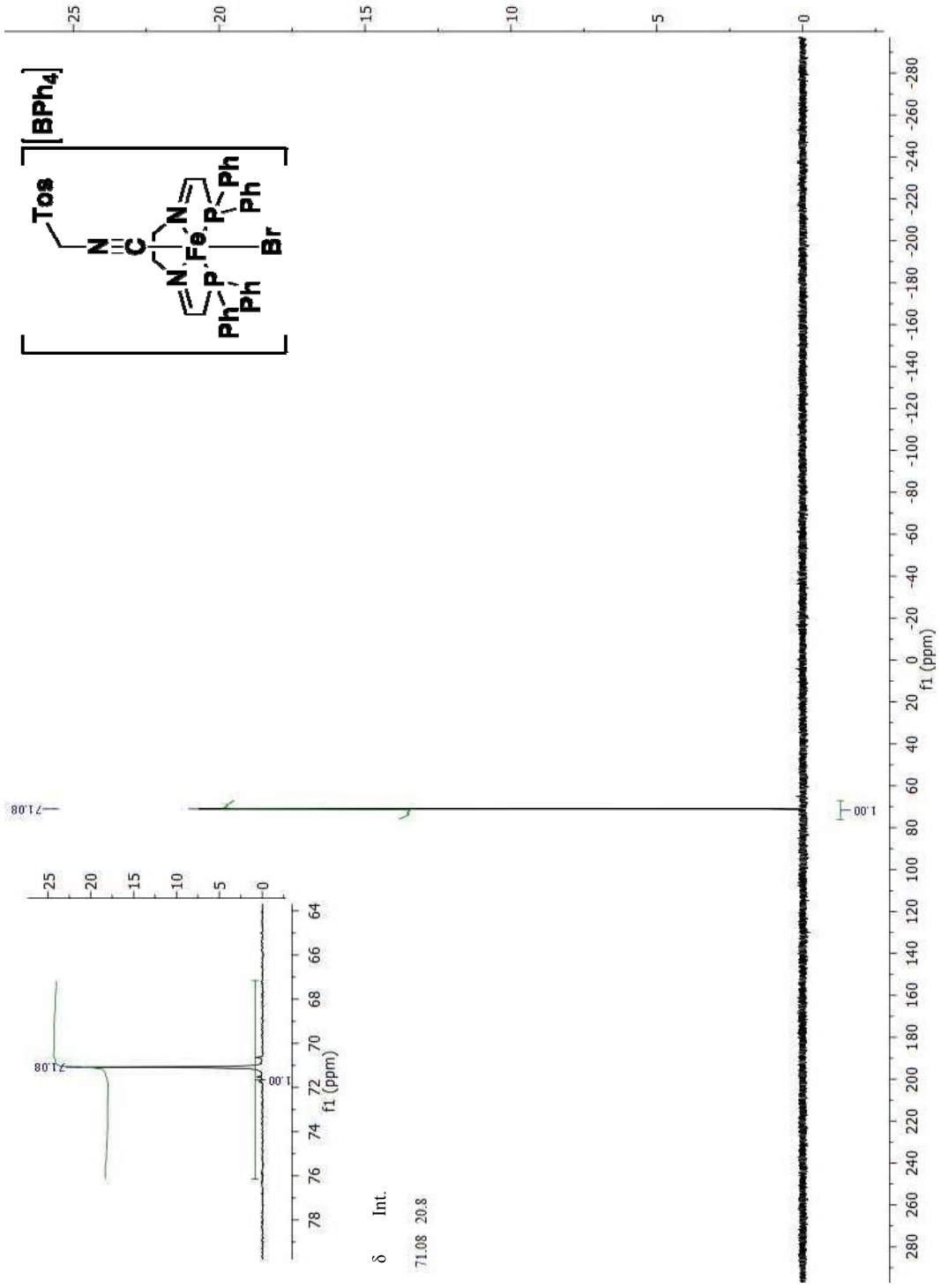


Figure S6. The infrared spectrum of the tetradentate PNNP, isocyanide iron complex as a KBr disc

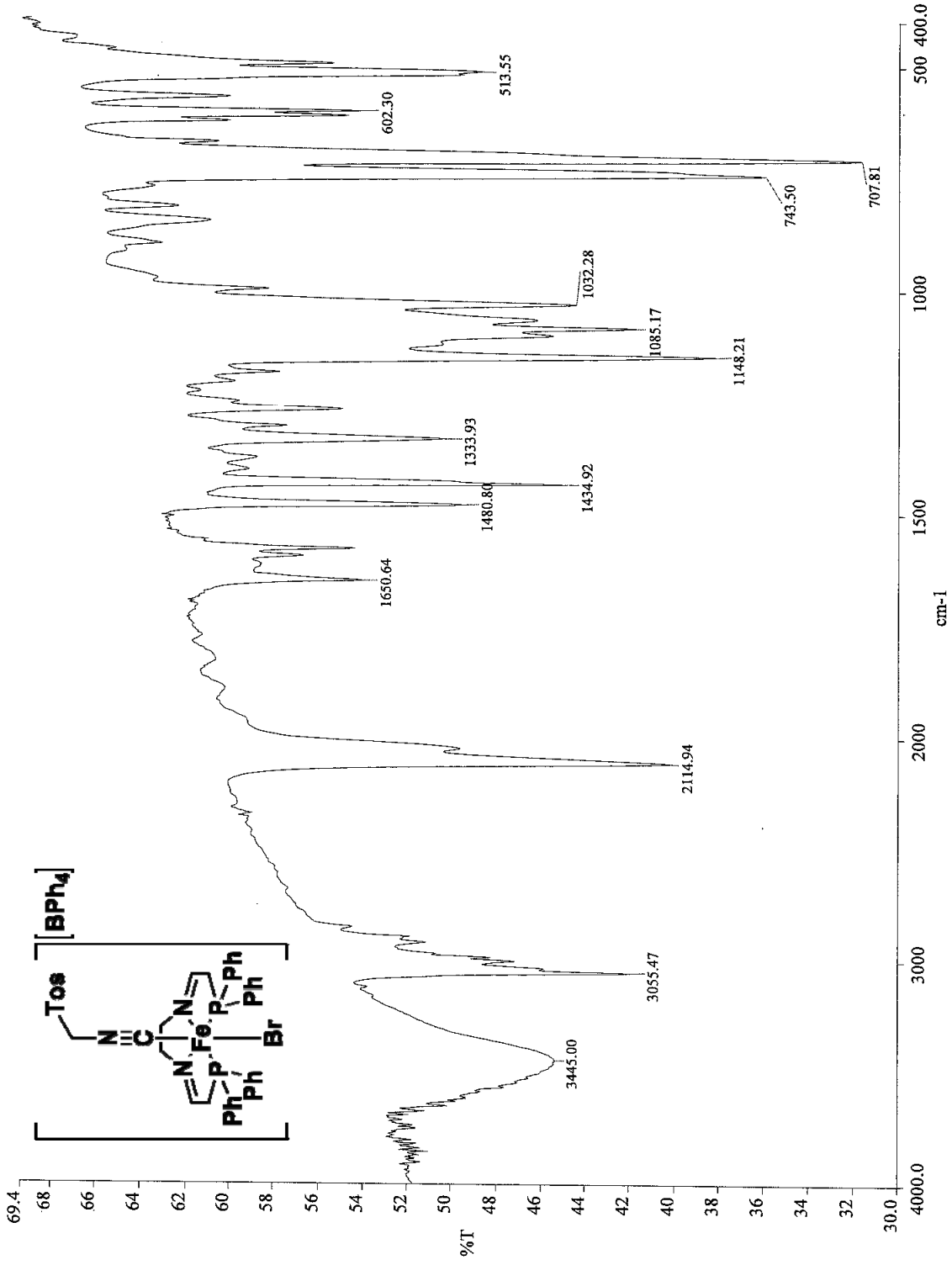
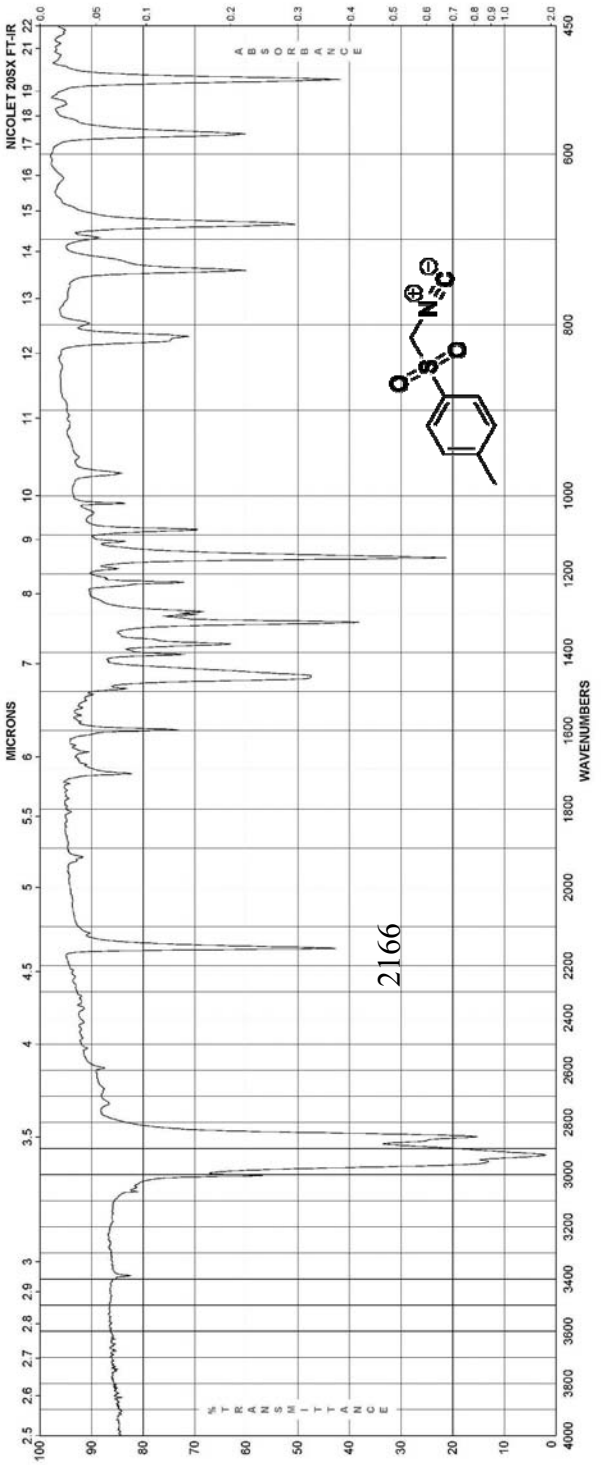


Figure S7. The infrared spectrum of the *p*-toluenesulfonylmethyl isocyanide starting material as a KBr disc.[16]



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Demonstrator Notes

Part 1: Experimental Procedure Notes

- The order of addition is somewhat important in that the iron source and phosphonium dimer need to be added first, and then the base should be added. If the phosphonium dimer is deprotonated without the iron template present, and left for a period of time, it will decompose and form oligomers.

- When the base is added to the iron/dimer mixture, you will see a dark greenish colour (unavoidable), which should rapidly disappear and become pale yellow or colourless. You can gauge how well the students have excluded oxygen by how dark the solution becomes, and how long it takes to disappear; the darker it turns, and the longer it takes to disappear, the more oxygen in the reaction vessel.

- When the diamine is added the solution should rapidly turn a dark red/purple colour. As the solution is heated, this colour should become a deep reddish/orange.

- When the tetraphenylborate is added, often times the precipitate will form a gummy ball on the stir bar. This is normal. Get the students to break up the mass as they wash with MeOH and ether.

- It should be noted that this experiment works in a flask open to air. The only difference is that the final yield decreases drastically. As such, the yield of the product is a good measure of how well the students excluded oxygen throughout the experiment.

- Typical yields are around 80-85%.

- In their discussion section, students should recognize the reaction of the aldehyde end of the coordinated phosphine with ethylenediamine (a primary amine), in forming the imine, as a **Schiff base** reaction. This results in the condensation of 1 equivalent of H_2O per N centre.

- A note on stoichiometry: 1.5 equivalents of iron are added to accommodate the formation of tetrabromoferrate. This also why a salt metathesis is performed; because, otherwise, there is a mixture of counter-ions.

Part 1: Stoichiometry and Yield Calculations

$$3\ [Fe(H_2O)_6][BF_4]_2(al)\ +\ 2\ [P(C_6H_5)_2CH_2CHOH]_2[Br]_2(al)\ +\ 4\ KOH(al)$$

$$+\ 2\ H_2NCH_2CH_2NH_2(an)\ +\ 4\ CH_3CN(an)\ +\ 4\ NaB(C_6H_5)_4(al)$$

$$\downarrow$$

$$2\ [Fe(CH_2NCHCH_2P(C_6H_5)_2)_2(CH_3CN)_2][B(C_6H_5)_4]_2(s)$$

$$+\ 4\ K^+(al)\ +\ 4\ Na^+(al)\ +\ [FeBr_4]^{2-}(al)\ +\ 6\ [BF_4]^-(al)\ +\ 26\ H_2O(al)$$

$$al\ =\ CH_3OH \qquad an\ =\ CH_3CN$$

Table S1. Amounts and Number of Equivalents of the Starting Materials used in Part A.

Compound	FW (g/mol)	Amount	No. mmol (equivalents)
$[Fe(H_2O)_6][BF_4]_2$	337.55	0.13 g	0.39 (3)
Phosphonium dimer $[P(C_6H_5)_2CH_2CHOH]_2[Br]_2$	618.28	0.16 g	0.26 (2)
KOH	56.11	(2 mL)(0.26 M)	0.52 (4)
CH_3CN	41.05	(1 mL)(0.786 g/mL)	19.15
$H_2NCH_2CH_2NH_2$	60.10	(1 mL)(0.26 M)	0.26 (2)
$NaB(C_6H_5)_4$	342.23	0.20 g	0.58 (4.5)
$[Fe(CH_2NCHCH_2P(C_6H_5)_2)_2(H_3CCN)_2][B(C_6H_5)_4]_2$	1256.92	0.33 g	0.26 (2)

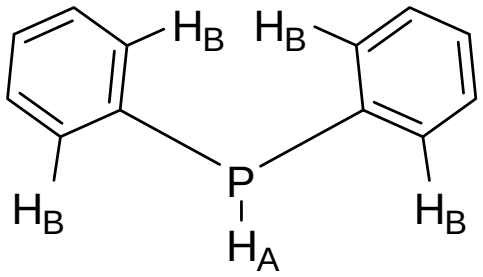
Part 1: Exercises

Figures S2, S3 and S4 show the ^{31}P spectra of (a) diphenylphosphine (b) the phosphonium dimer and (c) the tetradentate iron(II) complex, respectively. Note that only Figure S2 displays a proton-coupled phosphorus pattern. The others are proton-decoupled spectra. Refer to these figures in answering the following questions.

(1) For diphenylphosphine, explain the origin of the splitting pattern (doublet of quintets) observed for the single phosphorus nucleus.

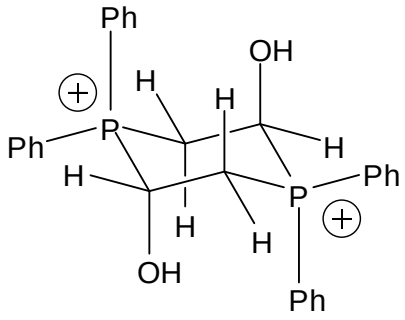
Answer:

The large coupling constant is from the hydrogen directly bonded to the phosphorus centre (H_A, 1-bond coupling), while the smaller coupling constant is from the four chemically equivalent hydrogens in the *ortho*-positions (H_B, 3-bond coupling).

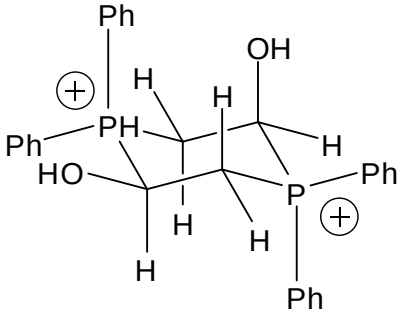


(2) Structurally, the phosphonium dimer adopts a chair conformation similar to that of cyclohexane. Taking stereochemistry into account, draw all the possible chair conformations.

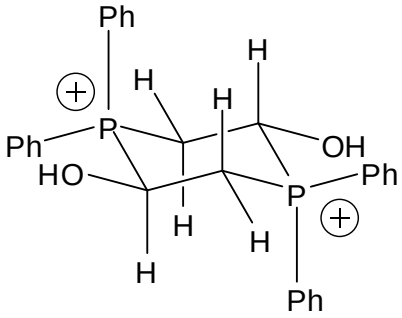
Answer:



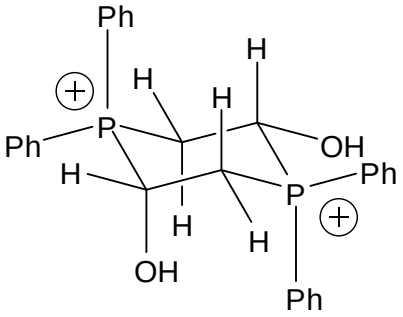
R, S



S, S



S, R



R, R

Note: The *R, R* and *S, S* structures are equivalent, or meso.

(3) Using your answer to (2) as a guide, account for the origin of the two observed peaks in the ^{31}P NMR spectrum of the pure compound. Is the synthesis of the phosphonium dimer a stereospecific reaction?

Answer:

The two observed peaks are for the two diastereomers that are formed in the reaction. The reaction is slightly stereoselective, but not stereospecific.

(4) Tabulate the chemical shifts of the phosphorus signals for the three compounds (you may use an average value for diphenylphosphine). Note the trend in these values and account for it in terms of the chemical environment around the phosphorus centres.

Answer:

Compound	Chemical Shift (ppm)
Diphenylphosphine	– 40.23
Phosphonium dimer	16.41 11.57
Iron PNNP complex	73.00

- On going from the diphenylphosphine to the phosphonium dimer to the metal complex the phosphorus chemical shift goes further and further downfield. This is representative of the shielding or electron density of the phosphorus centre.

- The free phosphine is the most electron rich and therefore is the furthest upfield (negative region). The phosphonium dimer is less electron rich than the free phosphine because the phosphorus lone pair is shared between the carbon and phosphorus nuclei (forms a P–C bond). In addition the two phosphorus centres each bear a positive charge in the dimer.

- Lastly, the metal complex has the most downfield shift. The iron binds the phosphorus lone pair, which is shared between the metal and phosphorus nuclei, to form a Fe–P bond. The metal ion is positively charged and is a much stronger Lewis acid than a carbon atom, so the metal pulls more electron density from the phosphorus centre, greatly deshielding it, in comparison to the phosphonium dimer.

Part 2: Experimental Procedure Notes

- The order of addition is somewhat important as well. Make sure the iron complex and KBr are together before adding the isocyanide, or a mixture of products might form (two isocyanide ligands bind).

- Be careful the students do not evaporate all of the acetone while they are heating their solutions. If the level of solvent drops drastically, add another few millilitres of acetone.

- As the reaction proceeds the colour changes from orange to yellow and a large amount of yellow precipitate usually forms. If not, this is not an indication the reaction is not working; occasionally no precipitate forms for unknown reasons. Follow the procedure, and the complex will crash out of solution upon addition of pentane or hexanes.

- Typical yields are around 80%.

Part 2: Stoichiometry and Yield Calculations

$$[Fe(CH_2NCHCH_2P(C_6H_5)_2)_2(H_3CCN)_2][B(C_6H_5)_4]_2(ac)$$

$$+ \text{ p-}CH_3C_6H_4SO_2CH_2NC(ac) + KBr(ac)$$

$$\downarrow$$

$$[Fe(CH_2NCHCH_2P(C_6H_5)_2)_2(CH_3C_6H_4SO_2CH_2NC)Br][B(C_6H_5)_4](ac)$$

$$+ K^+(ac) + [B(C_6H_5)_4]^-(ac) + 2\ CH_3CN(ac)$$

$$ac = CH_3COCH_3$$

Table S2. Amounts and Number of Equivalents of the Starting Materials used in Part B.

Compound	FW (g/mol)	Amount	No. mmol (equivalents)
$[Fe(CH_2NCHCH_2P(C_6H_5)_2)_2(H_3CCN)_2][B(C_6H_5)_4]_2$	1256.92	0.15 g	0.12 (1)
KBr	119.01	0.2 g	1.7
p-$CH_3C_6H_4SO_2CH_2NC$	195.24	(5 mL)(0.025 M)	0.12 (1)
$[Fe(CH_2NCHCH_2P(C_6H_5)_2)_2(CH_3C_6H_4SO_2CH_2NC)Br][B(C_6H_5)_4]$	1130.73	0.14 g	0.12 (1)

Part 2: Infrared Analysis Summary

p-tosylmethyl isocyanide: $\nu(C\equiv N) = 2166\ cm^{-1}$

Part B product: $\nu(C\equiv N) = 2115\ cm^{-1}$

Part 2: Exercises

Figures S5 and S6 show the ^{31}P NMR and the infrared spectrum of the final product, respectively. Figure S7 displays the infrared spectrum of the free p-toluenesulfonylmethyl isocyanide. Refer to these figures in answering the following exercises.

(5) Account for the shift in the wavenumber of the C≡N bond stretch of the final complex compared with that of the free ligand. Would you expect the bromide ligand to play a role in affecting this value? If so, in what manner?

Answer:

p-tosylmethyl isocyanide:	ν(C≡N)	=	2166 cm^{-1}
Part B product:	ν(C≡N)	=	2115 cm^{-1}

The shift in the wavenumber, ie. the fact that it shifts to a lower value, is due to back donation from the metal centre. Much like CO, the isocyanide ligand has a low energy anti-bonding (π^*) orbital that the iron centre can donate d-electrons into. This weakens the C≡N bond and accounts for the shift from the free ligand. The bromide also plays a role in decreasing this value. Firstly, the bromide is negatively charged, and thus decreases the overall charge of the iron complex and makes the iron centre more electron rich. In addition, the bromide is a π-donor, which causes repulsion between the bromide lone pairs (filled p orbitals) and filled d-orbitals on the metal. This helps "push" electron density into the anti-bonding (π^*) orbital of the trans isocyanide ligand, away from the bromide lone pairs.

(6) Compare the chemical shift of the phosphorus centres in the products of parts (A) and (B). Explain the similar values keeping in mind the following factors: (a) charge on the complex ion and (b) π acceptor abilities of the trans ligands (note: acetonitrile is generally considered to be a good σ donor but a very poor π acceptor).

Answer:

Compound	Chemical Shift (ppm)
Product from Part A	73.00
Product from Part B	71.08

The *trans* ligands for both of these species are very different, but despite this the phosphorus shifts are very similar. The product from Part A has a 2+ charge, while the product from Part B has a 1+ charge. Based on this you would expect the product from Part B to be more electron rich, and the phosphorus nuclei to be more shielded (more upfield). The isocyanide ligand, however, is a very strong π-acceptor, and thus pulls electron density away from the metal centre, making it more electron deficient. The acetonitrile ligands in the product of Part A, on the other hand, are weak π-acceptors, and good σ donors, so they do not pull electron density from the metal centre. This helps counterbalance the difference in charge between the two species, such that the phosphorus nuclei are not significantly more shielded in the product from Part B than they are in the product from Part A.

(7) Taking into account the oxidation state of the metal and the number of ligands coordinated to it, calculate the total electron count on the iron centre for the products of both parts of this experiment.

Answer:

The electron counts for both products are the same. They are both octahedral iron(II) metal centres (d^6) with 6 ligands, therefore they are 6 + 6*2 = 18 electron species.

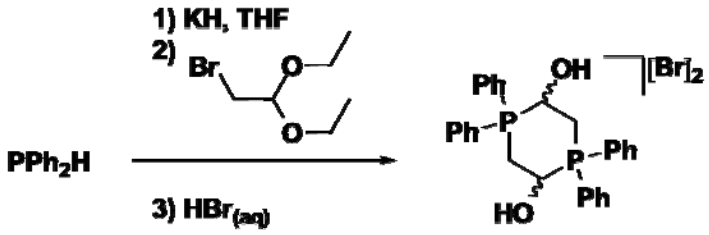
(8) Using your answer to (7) as a guide, would you expect the ligand substitution reactions to proceed through an associative or dissociative mechanism? Explain your reasoning.

Answer:

You would expect the ligand substitution reactions to proceed through a dissociative mechanism rather than an associative mechanism because the iron centres are coordinatively saturated 18 electron species. It is much easier for a ligand to dissociate and transiently form a 16 electron species (many 16 electron species known) than it is for an additional ligand to bind and form a 20 electron species (almost unheard of). In addition, the sample is heated to help ligands dissociate.

Synthesis of the Phosphonium Dimer 1

Scheme S8. Synthesis of Phosphonium Dimer 1.



Experimental Procedure. A Schlenk flask was charged with KH (1 eq.) and dry THF (2.5 mL/0.100 g KH). Diphenylphosphine (1 eq.) was added, and the solution turned red in color. The solution was stirred for 30 min and then cooled to 0°C. Bromoacetadehyde diethyl acetal (1 eq.) was added over 20 min, and the solution turned yellow. The solution was warmed to room temperature and 48% HBr (excess) was added. A white precipitate formed and the solution turned colorless. The mixture was left stirring for 2 hours, and then placed in a freezer (-40ºC) for an hour. The precipitate was filtered off and washed with H_2O (2x15 mL), as well as ethyl acetate (15 mL). The precipitate was dried under high vacuum.