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Abstract

The addition of phosphonate stabilized carbon nucleophiles to acyclic (pentadienyl)iron(1+) cations proceeds predominantly at an internal carbon to afford (pentenediyl)iron complexes. Those complexes bearing an electron withdrawing group at the σ-bound carbon (i.e., **13/14**) are stable and isolable, while complexes which do not contain an electron withdrawing group at the σ-bound carbon undergo CO insertion, reductive elimination and conjugation of the double bond to afford cyclohexenone products (**21/22**). Deprotonation of the phosphonate **13/14** or **21** and reaction with paraformaldehyde affords the olefinated products. This methodology was utilized to prepare oxygenated carvone metabolites (±)-**25** and (±)-**26**.

Graphical abstract
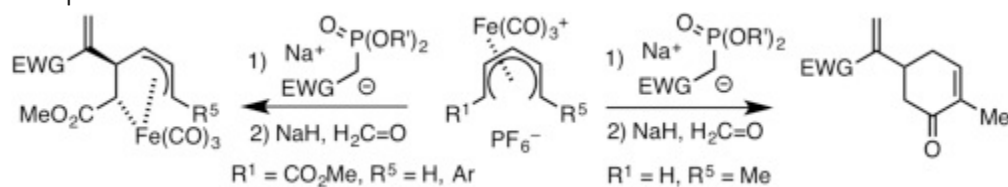
Keywords

Dienyl-iron cations, Nucleophilic addition, Horner–Emmons olefination, Cyclocarbonylation, Terpenes

1. Introduction

Nucleophilic addition to cationic polyenyl-metal complexes is an exemplar of organometallic chemistry. Where these reactions proceed in good yield and with high regioselectivity, they have been utilized in organic synthesis.[1] There are numerous examples of the reaction of (cyclohexadienyl)- and (cycloheptadienyl)Fe(1+) cations (**1a–d**, Eq. 1) with stabilized carbon nucleophiles such as malonates,[2a–i] β-ketoesters,[2k–m] β-diketones,[2n–p] 2-cyano acetates,[2q–r] and arylsulfonyl acetates.[2s–t]
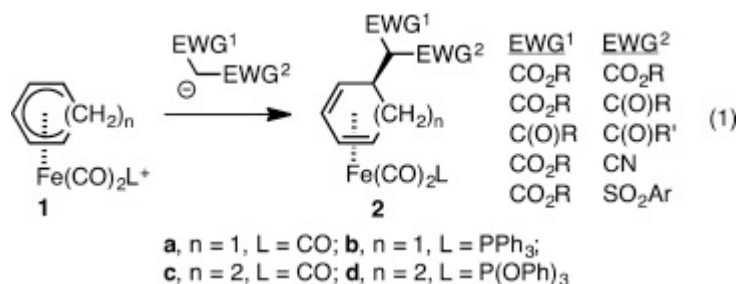
In spite of their potential as synthons for Horner–Emmons olefination, there are few examples of the reaction of dienyl-iron cations[3] or other organometallic cations[4] with phosphonate stabilized carbon nucleophiles. Stephenson, et al., reported the reaction of (cyclohexadienyl)Fe(CO)₃⁺ cations **3a/b** with the potassium salt of α-phosphoramide acetates proceeded with good regioselectivity, but in only

modest yields (Eq. 2).[3] Furthermore, the products **4** were not further processed into the corresponding alkenes via reduction of the ester and subsequent elimination.

3a, R = H
3b, R = OMe

4a, R = H, R' = Me (46%)
4b, R = OMe, R' = CH$_2$CH$_2$CH=CMe$_2$ (50%)
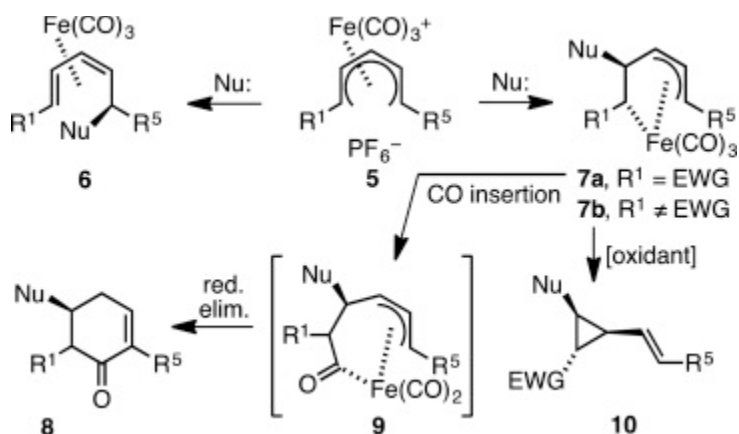
(2)
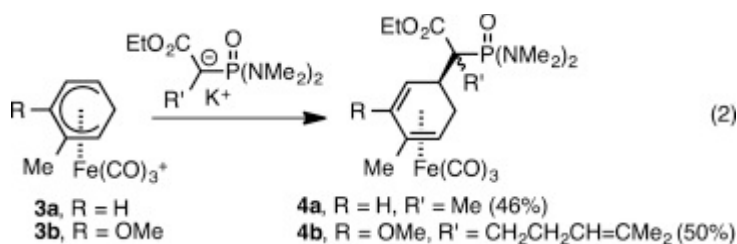
We and others have examined the reactivity of acyclic (pentadienyl)iron(1+) cations **5** with nucleophiles.[5] While certain nucleophiles attack at the pentadienyl terminus to generate *E,Z*-diene complexes **6**, other nucleophiles react via attack at an internal pentadienyl carbon to generate 2-substituted (3-pentene-1,5-diyl)Fe complexes **7**. This latter reactivity is relatively unique to acyclic (pentadienyl)Fe$^+$ cations compared to their cyclic counterparts **1**. Complexes **7a**, in which the R^1 substituent attached to the iron-bonded sp^{3}carbon is not an electron-withdrawing group, are not stable and these eventually decompose to cyclohexenone products **8**, via CO insertion followed by reductive elimination and olefin isomerization.[6,7] In contrast, those complexes **7b** which possess an electron-withdrawing R^1 substituent are stable, isolable species which are resistant to CO insertion. Oxidatively induced-reductive elimination of complexes **7b** generate vinylcyclopropane-carboxylates **10**.[8]

We herein report on the reaction of acyclic (pentadienyl)iron cations with phosphonate stabilized carbon nucleophiles, culminating in an application to the synthesis of oxygenated metabolites of carvone.
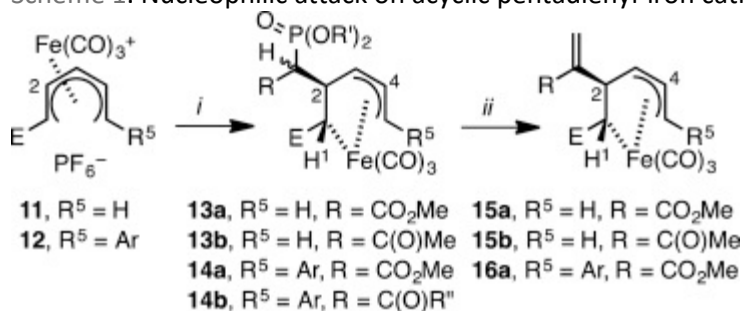
2. Results and discussion[9]

Addition of the anion generated from trimethyl phosphonoacetate or diethyl (2-oxopropyl)phosphonate to (1-methoxypentadienyl)iron cation (**11**)[10]proceeded at the C2 carbon to afford the 2-substituted (pentenediyl)iron complexes **13a** or **13b** ([Scheme 2], [Table 1]). In a similar fashion, addition of the anions generated from trimethyl phosphonoacetate or [6-(*t*-butyldiphenylsilyl)oxy]-2-oxohexylphosphonic acid dimethyl ester[11] with cation (**12**)[8k] afforded the (pentenediyl)iron complexes **14a** or **14b**. Complexes **13a**, **13b**, **14a**, **14b** were obtained as inseparable mixtures of diastereomers at the indicated (*) carbon, as determined by ^{1}H NMR spectroscopy. Each exhibited two doublet signals in the range δ 0.01–0.80 ppm which were assigned to the hydrogen attached to the σ-bound carbon (H^1) of each diastereomer.[8c,i,k] That **13a**, **14a**, and **13b** were

diastereomeric at the indicted carbon was further corroborated by their conversion to a single enoate or enone (**15a**, **16a** or **15b**) upon Horner–Emmons olefination with paraformaldehyde.

Scheme 1. Nucleophilic attack on acyclic pentadienyl-iron cations **5**.

11, R^5 = H   13a, R^5 = H, R = CO$_2$Me   15a, R^5 = H, R = CO$_2$Me
12, R^5 = Ar   13b, R^5 = H, R = C(O)Me   15b, R^5 = H, R = C(O)Me
                  14a, R^5 = Ar, R = CO$_2$Me   16a, R^5 = Ar, R = CO$_2$Me
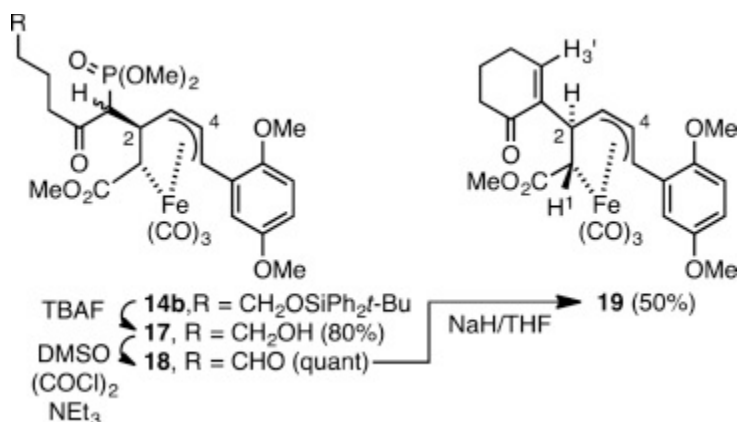   14b, R^5 = Ar, R = C(O)R"

Scheme 2. Addition of phosphonate stabilized nucleophiles to (1-methoxycarbonylpentadienyl)iron(1+) cations, and subsequent HWE olefination. Ar=2,5-dimethoxyphenyl; R"=(CH$_2$)$_4$OSiPh$_2$t-Bu. Reagents: *i*) Na$^+$ – CH[P(O)(OR')$_2$R]; *ii*) base, paraformaldehyde.

Table 1. Addition of phosphonate stabilized nucleophiles to (1-methoxycarbonylpentadienyl)iron(1+) cations, and subsequent HWE olefination (E=CO$_2$Me)

R^5	R	R'	Product (yield)	Base	Product (yield)
H	CO$_2$Me	Me	**13a** (69%)	NaH	**15a** (84%)
H	C(O)Me	Et	**13b** (66%)	NaH	**15b** (50%)
Ar	CO$_2$Me	Me	**14a** (85%)	*n*-BuLi	**16a** (90%)
Ar	C(O)R"	Me	**14b** (98%)		

Ar=2,5-dimethoxyphenyl; R"=(CH$_2$)$_4$OSiPh$_2$t-Bu.

Deprotection of the silyl ether of alkylated β-ketophosphonate **14b**, gave the alcohol **17** ([Scheme 3](#)), which upon Swern oxidation afforded aldehyde **18**; both **17** and **18** were obtained as a mixture of diastereomers. Subsequent intramolecular Horner–Emmons olefination of **18** gave the cyclohexenone **19**as a single diastereomer. Notably, a signal at δ 6.20 ppm in the ^{1}H NMR spectrum corresponds to H3' and signals at δ 198.4, 143.9, and 141.8 ppm in the ^{13}C NMR spectrum correspond to the carbonyl and olefinic carbons of the cyclohexenone fragment.

R
O=P(OMe)$_2$
H
OMe
2   4
MeO$_2$C
Fe
(CO)$_3$
OMe

H$_3$'
H
OMe
2   4
MeO$_2$C
H^1 Fe
(CO)$_3$
OMe

TBAF **14b**,R = CH$_2$OSiPh$_2$t-Bu
17, R = CH$_2$OH (80%)   NaH/THF   **19** (50%)
DMSO **18**, R = CHO (quant)
(COCl)$_2$
NEt$_3$

Scheme 3. Intramolecular Horner–Emmons olefination to generate cyclohexenone (pentenediyl)iron complex **19**.

The regioselectivity for addition of the phosphonate stabilized nucleophiles to cation **11** is similar to the addition of malonate, arylsulfonyl acetates and alkenyl Grignards to this same cation.[8a,c,e,f,i] In contrast, the regioselectivity for addition to **12** is considerably greater than that for addition of alkenyl Grignards to this cation.[8k] Additionally, the functionality introduced onto the (pentenediyl) ligand by the present sequence of nucleophilic addition/Horner–Emmons olefination would not be available within an alkenyl Grignard reagent.

In contrast to the above results, reaction of (pentadienyl)iron cation **20** with sodium trimethyl phosphonylacetate gave a mixture of regioisomeric cyclohexenones **21a/22a**, each of which consisted of a mixture of diastereomers at the indicated (*) carbon ([Scheme 4](#), [Table 2](#)). The ratio of **21a:22a** was determined by integration of the ^{1}H NMR signals for H3 of **21a**compared to the integration of the H3 signal for **22a**. Olefination of the mixture of **21a/22a** with paraformaldehyde gave a mixture of **23a/24a**; a pure sample of **23a** could be obtained by column chromatography. In a similar fashion, reaction of **20** with sodium diethyl (2-oxopropyl)phosphonate or with sodium diethyl (phenylsulfonyl)-methanephosphonate gave a mixture of **21b/22b** or **21c** respectively; each of which consisted of a mixture of diastereomers. Olefination of the mixture of **21b/22b** with formaldehyde gave a mixture of **23b/24b**, while olefination of **21c** gave the vinylsulfonate **23c**. The structures of **21** and **23** were

assigned as 5-substituted-2-methylcyclohexenones on the basis of their NMR spectral data. In particular, the signals for H-3 and the Me-2 appear at ca. δ 6.7–6.6 (m) and 1.75–1.80 (s) ppm, respectively, in their ^{1}H NMR spectra, while the signals for C1, C2, C3 and Me-2 appear at ca. δ 199, 135, 144, and 15.9 ppm, respectively, in their ^{13}C NMR spectra.
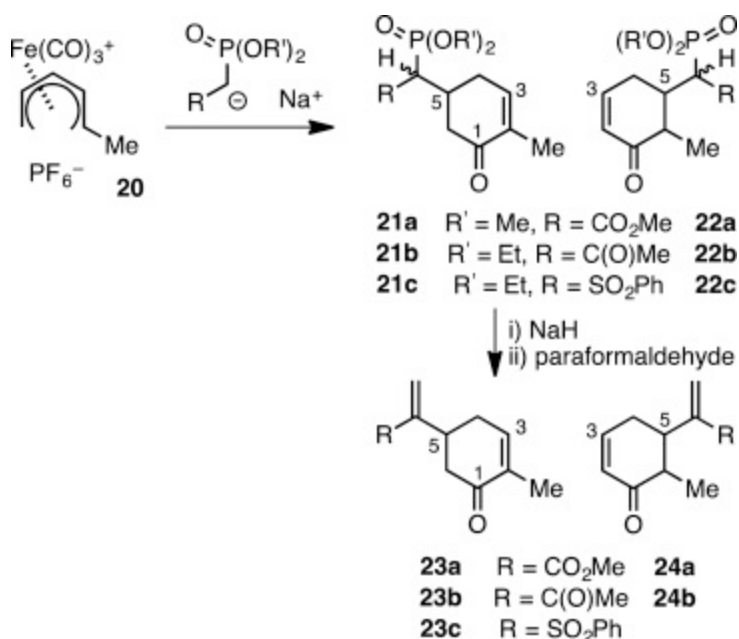
Scheme 4. Addition of phosphonate stabilized nucleophiles to (1-methylpentadienyl)Fe(CO)$_3$$^+$ cation.

Table 2. Addition of phosphonate stabilized nucleophiles to (1-methylpentadienyl)iron(1+) cations, and subsequent HWE olefination[a]

R	OR'	Product (ratio,[a] yield)	Product (ratio,[a] yield)
CO$_2$Me	OMe	21a+22a (10:1, 87%)	23a+24a (10:1, 69%)
COMe	OEt	21b+22b (6:1, 74%)	23b+24b (6:1, 89%)
SO$_2$Ph	OEt	21c (47%)	23c (72%)

[a]Ratio of constitutional isomeric products determined by ^{1}H NMR integration of the β-hydrogen signals.

Formation of cyclohexenone product 21 is rationalized by nucleophilic attack at an internal pentadienyl carbon of 20 to afford the (pentenediyl)iron complex 9 (R^1=H, R^5=Me, Scheme 1). Carbonyl insertion followed by reductive elimination and subsequent conjugation of the double bond affords 21. 10-Hydroxycarvone (25, Scheme 5) has been isolated from *Hyssopus cuspidatus*, a plant used in Chinese folk medicine for the treatment of fever and broncusus asthma.[12a] This terpene has also been isolated as a minor carvone metabolite from cultured cells of the Madagascar periwinkle, *Catharanthus*

roseus,[12b] and as an excreted metabolite of carvone in the urine of rabbits,[13a] and human volunteers,[13b,c] while carvonic acid (**26**) has also been isolated as a human metabolite of carvone.[13b,c] 10-Hydroxycarvone has been prepared from carvone by regioselective chlorination at C10 and subsequent solvolysis of the halide.[14,15] Saponification of **23a** afforded carvonic acid **26**. Attempted reduction of **26** with borane gave a complex mixture of products. Alternatively, α-deprotonation of the cyclohexenone **23a** with LDA, followed by addition of DIBAL gave **25** after workup. The spectral data obtained for **25** and **26** were consistent with their literature values.[13b,14a]
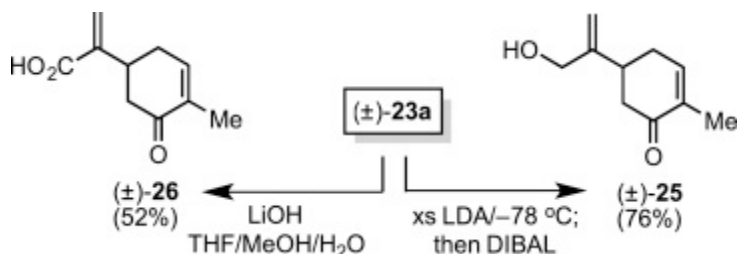
Scheme 5. **Synthesis of oxygenated metabolites of carvone.**

3. Conclusions

In contrast to the addition of α-phosphoramide acetate anions to (cyclohexadienyl)iron(1+) cations, the addition of phosphonate stabilized carbon nucleophiles to *acyclic* (pentadienyl)iron(1+) cations occurs primarily at an internal dienyl carbon to form (pentenediyl)iron complexes. The fate of the (pentenediyl)iron products depends on the presence or absence of an electron withdrawing ester substituent at the σ-bound carbon. Horner–Wadsworth–Emmons olefination of the phosphonate addition products generates (2-alkenyl-3-pentene-1,5-yl)iron complexes or 5-alkenyl-2-methyl-2-cyclohexenones. The latter are suitable precursors for the preparation of 10-hydroxycarvone and carvonic acid.

4. Experimental

4.1. General data

All reactions involving moisture or air sensitive reagents were carried out under an nitrogen atmosphere in oven-dried glassware with anhydrous solvents. THF and ether were distilled from sodium/benzophenone. Purifications by chromatography were carried out using flash silica gel (32–63 μ). NMR spectra were recorded on either a Varian Mercury+ 300 MHz or a Varian UnityInova 400 MHz instrument. CDCl$_3$, CD$_3$OD, d$_6$-acetone were purchased from Cambridge Isotope Laboratories. ^{1}H NMR spectra were calibrated to 7.27 ppm for residual CHCl$_3$, 3.31 ppm for CD$_2$HOD, or 2.05 ppm for d$_5$-acetone. ^{13}C NMR spectra were calibrated from the central peak at 77.23 ppm for CDCl$_3$, 49.15 ppm for CD$_3$OD, or 29.92 ppm for d$_6$-acetone. Coupling constants are reported in Hz.

Elemental analyses were obtained from Midwest Microlabs, Ltd., Indianapolis, IN, and high-resolution mass spectra were obtained from the University of Nebraska Center for Mass Spectrometry and the COSMIC lab at Old Dominion University.

4.2. Tricarbonyl(5-(methoxycarbonyl)-4-(1-methoxycarbonyldimethylphosphonomethyl)-2-penten-1,5-diyl)iron. (±)-13a

To a stirring suspension of sodium hydride (175 mg, 7.2 mmol) in dry THF (120 mL) at 0 °C under N_2, was added trimethyl phosphonoacetate (885 mg, 4.86 mmol). The reaction mixture was stirred for 30 min, and then a solution/suspension of (±)-**11** (2.00 g, 4.86 mmol) in dry THF (60 mL) was added. The reaction mixture was stirred overnight, and then quenched with water. The mixture was diluted with CH_2Cl_2 and the layers were separated. The aqueous layer was extracted once with CH_2Cl_2 and the combined organic extracts were washed once with saturated aqueous NaCl, and dried ($MgSO_4$), and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, ethyl acetate) to afford the product (±)-**13a** (372 mg, 69%) as a yellow oil; δ_H (400 MHz, $CDCl_3$) 4.69–4.39 (2H, m, H-3 and H-4), 3.81–3.55 (14H, m, $4 \times OCH_3$ and H-2 and H-6), 2.67–2.39 (2H, m, H-5exo and H-5endo), 0.33 and 0.01 (1H total, $2 \times d$, J 8.7 Hz each, H-1). δ_C (partial, 100 MHz, $CDCl_3$) 210.2, 209.9, 209.7, 209.6, 203.5, 203.3, 179.7, 179.6, 167.3 (d, J_{CP} 5.3 Hz), 166.7 (d, J_{CP} 4.7 Hz), 97.9, 97.4, 62.7, 62.6, 60.8, 60.6, 37.4 (J_{CP} 3.8 Hz), 37.0 (J_{CP} 4.0 Hz), 13.3 (J_{CP} 1.9 Hz), 12.1 (J_{CP} 14.1 Hz). HRMS (FAB): MNa^+–3CO, found 385.0110. $C_{12}H_{19}O_7PFeNa$ requires 385.0114.

4.3. Tricarbonyl(5-(methoxycarbonyl)-4-(1-diethylphosphono-2-oxopropyl)-2-penten-1,5-diyl)iron. (±)-13b

The reaction of the anion generated from diethyl (2-oxopropyl) phosphonate (240 mg, 1.21 mmol) and sodium hydride in dry THF with cation **11** (500 mg, 1.21 mmol) was carried out in a fashion similar to the preparation of **13a**. The residue was purified by column chromatography (SiO_2, ethyl acetate) to afford (±)-**13b** (365 mg, 66%) as a yellow oil; δ_H (400 MHz, $CDCl_3$) 4.79–4.50 (2H, m, H-3 and H-4), 4.29–4.05 (4H, m, $-OCH_2CH_3$), 4.01–3.87 and 3.72–3.63 (2H total, H-2 and H-6), 3.76 and 3.74 (3H total, $2 \times s$, OCH_3), 2.98–2.51 (2H, m, H-5exo and H-5endo), 2.37 and 2.18 (3H total, $2 \times s$, $COCH_3$), 1.48–1.31 (6H, m, $-OCH_2CH_3$), 0.44 and 0.01 (1H total, $2 \times d$, J 8.4 Hz each, H-1). δ_C (partial, 100 MHz, $CDCl_3$) 210.0 [209.7] (*CO*Me), 203.3 [203.2], 201.9 [201.8], 201.21 [201.20] (Fe–CO), 179.6 [179.5] ($-CO_2CH_3$), 97.0 [96.8] (C-4), 64.2, 61.7, 61.5, 54.4, 51.3 [51.2] ($-CO_2CH_3$), 36.5, 36.1, 32.3, 29.8, 12.5, 11.9 [11.8] (C-1). HRMS (FAB): MNa^+, found 397.0476. $C_{14}H_{23}O_6PFeNa$ requires 397.0474.

4.4. Tricarbonyl(5-(methoxycarbonyl)-4-(1-methoxycarbonyldimethylphosphonomethyl)-1-(2,5-dimethoxyphenyl)-2-penten-1,5-diyl)iron. (±)-14a

The anion generated from trimethyl phosphonoacetate (0.40 g, 2.2 mmol) and NaH (58 mg, 2.4 mmol) in dry THF (10 mL) at 0 °C was added by cannula to a solution of (±)-**12** (1.1 g, 2.0 mmol) in dry CH$_2$Cl$_2$ (50 mL) at −78 °C. After stirring for 1 h at −78 °C, the reaction mixture was slowly warmed to room temperature, and then quenched with saturated aqueous NH$_4$Cl. Workup of the reaction mixture was similar to that for **13a**. The residue was purified by column chromatography (SiO$_2$, gradient ethyl acetate→ethyl acetate–methanol=4:1) to afford (±)-**14a** as a yellow solid (0.99 g, 85%). An analytically pure mixture of diastereomers (ca. 2:1 ratio) was obtained by recrystallization from CH$_2$Cl$_2$/hexanes; mp 150–151 °C; [Found: C, 47.37; H, 4.92. C$_{23}$H$_{30}$O$_{12}$PFe requires C, 47.20; H, 5.17%]; δ_H (400 MHz, CDCl$_3$) major diastereomer 6.70–6.85 (3H, m, ArH), 5.27 (1H, dd, J 7.2, 12.7 Hz, H-4), 4.66 (1H, d, J 12.8 Hz, H-5), 4.32 (1H, t, J 7.2 Hz, H-3), 3.87, 3.72, 3.69, 3.67 (19H total, 4×s & m, OCH_3 and H-2), 2.71 (1H, dd, $^3J_{HH}$ 11.3, $^2J_{PH}$ 20.6 Hz, CH(CO$_2$Me)P(O)(OMe)$_2$), 0.77 (1H, d, J 8.5 Hz, H-1); minor diastereomer: 6.85–6.70 (3H, m, ArH), 5.33 (1H, dd, J 7.2, 12.7 Hz, H-4), 4.61 (1H, d, J 12.8 Hz, H-5), 4.52 (1H, t, J 7.2 Hz, H-3), 3.76, 3.74, 3.69, 3.67, 3.64, 3.59 (19H, 6×s & m, OCH$_3$ and H-2), 2.69 (1H, dd, $^3J_{HH}$ 11.3, $^2J_{PH}$ 20.6 Hz, CH(CO$_2$Me)P(O)(OMe)$_2$), 0.44 (1H, d, J 8.5 Hz, H-1); δ_C (100 MHz, CDCl$_3$) major diastereomer: 210.2, 209.4, 203.7, 179.8, 167.4 (J_{CP} 5.2 Hz), 153.6, 151.3, 128.3, 113.4, 111.5, 109.4, 93.5, 70.2, 55.9, 55.8, 54.7, 54.0, 53.4, 53.3, 52.8, 52.5, 51.4, 37.0 (J_{CP} 7.5 Hz), 12.8 (J_{CP} 8.5 Hz); minor diastereomer: 210.0, 209.4, 203.8, 179.7, 166.8 (J_{CP} 4.9 Hz), 153.6, 151.3, 128.3, 113.4, 111.5, 109.4, 93.0, 56.2, 55.9, 54.8, 54.5, 53.6, 53.5, 52.7, 51.4, 37.5 (J_{CP} 4.2 Hz), 11.6 (J_{CP} 13.9 Hz); δ_P (CDCl$_3$, 162 MHz) 21.4 (major), 21.6 (minor).

4.5. Tricarbonyl[4-(6-t-butyldiphenylsilyloxy-1-(dimethylphosphonyl)-2-oxohexyl)-5-methoxycarbonyl-1-(2,5-dimethoxyphenyl)-2-penten-1,5-diyl]iron. (±)-14b

A solution of the anion prepared from [6-(*t*-butyldiphenyl-silyl)oxy]-2-oxohexylphosphonic acid dimethyl ester (0.46 g, 1.0 mmol) and NaH (48 mg, 1.2 mmol) in dry THF (30 mL) at 0 °C, was subsequently cooled to −78 °C and a solution of (±)-**12** (0.82 g, 1.5 mmol) in dry CH$_2$Cl$_2$ (50 mL) was added with stirring. Workup of the reaction mixture was similar to that for **14a**. The residue was purified by column chromatography (SiO$_2$, hexanes–ethyl acetate=4:1→2:1 gradient) to afford an equimolar mixture of diastereomers (±)-**14b** (0.85 g, 98%) as a yellow solid; mp 44–46 °C; [Found: C, 58.37; H, 5.99. C$_{42}$H$_{54}$O$_{12}$PSiFe requires C, 58.27; H, 6.29%]; δ_H (400 MHz, CDCl$_3$) 7.68–7.62 (4H, m, SiPh_2), 7.43–7.33 (6H, m, SiPh_2), 6.88–6.79 (3H, m, ArH), 5.35 and 5.15 (1H total, 2×dd, J 7.2, 12.8 Hz each, H-4), 4.70 and 4.64 (1H total, 2×d, J 12.8 Hz each, H-5), 4.57 and 4.30 (1H total, 2×t, J 7.2 Hz each, H-3), 3.92, 3.86, 3.79, 3.76, 3.74, 3.73, 3.72, 3.71, 3.67 and 3.65 (17H total, 10×s and m, OCH_3 and CH_2OSi),

3.00 (0.5H, dd, $^3J_{HH}$ 11.7, $^2J_{PH}$ 22.0 Hz, CH(COR)P(O)(OMe)$_2$), 2.92 (0.5H, dd, $^3J_{HH}$ 11.8, $^2J_{PH}$ 21.3 Hz, CH(COR)P(O)(OMe)$_2$), 2.73–2.64 (1H, m), 2.40–2.30 (1H, m), 1.75–1.45 (4H, m), 1.022 and 1.018 (9H, 2×s, SiC(CH_3)$_3$), 0.80 and 0.33 (1H total, 2×d, J 8.4 Hz each, H-1); δ_P (162 MHz, CDCl$_3$) 21.0, 22.0. Due to the presence of two diastereomers, as well as ^{31}P coupling, interpretation of the ^{13}C NMR spectrum was not attempted.

4.6. Tricarbonyl(4-(1-methoxycarbonylethenyl)-5-(methoxycarbonyl)-2-penten-1,5-diyl)iron. (±)-15a

To a solution of (±)-**13a** (40 mg, 0.088 mmol) in dry THF (3 mL) at 0 °C was added NaH (2.6 mg). The mixture was stirred for 15 min, and then paraformaldehyde (2.6 mg, 0.11 mmol) was added at 0 °C. The reaction mixture was warmed to room temperature over a 3 h period and then quenched with H$_2$O. The mixture was diluted with CH$_2$Cl$_2$ and the layers were separated. The aqueous layer was extracted once with CH$_2$Cl$_2$ and the combined organic extracts were washed once with saturated aqueous NaCl, and dried (MgSO$_4$), and concentrated under reduced pressure. The residue was purified by column chromatography (SiO$_2$, hexanes–ethyl acetate=17:3) to afford (±)-**15a** (25 mg, 84%) as a yellow oil which solidified in the refrigerator. δ_H (400 MHz, CDCl$_3$) 6.08 (1H, d, J 1.2 Hz, C=CH$_2$), 5.36 (1H, d, J 1.6 Hz, C=CH$_2$), 4.70 (1H, td, J 7.4, 12.0 Hz, H-4), 4.60 (1H, t, J 7.2 Hz, H-3), 4.11 (1H, br t, J 8.2 Hz, H-2), 3.72 (3H, s, OCH_3), 3.69 (3H, s, OCH_3), 3.48 (1H, td, J 1.8, 7.6 Hz, H-5exo), 2.21 (1H, dd, J 2.0, 12.4 Hz, H-5endo), 0.34 (1H, d, J 8.8 Hz, H-1). δ_C (100 MHz, CDCl$_3$) 211.0, 210.4, 204.1, 180.1, 166.3, 142.7, 123.5, 97.8, 62.1, 53.9, 51.7, 51.3, 40.0, 11.0. HRMS (FAB): M$_2$Na$^+$–6CO, found 555.0386. (C$_{11}$H$_{14}$O$_4$Fe)$_2$Na requires 555.0386.

4.7. Tricarbonyl(4-(1-methenyl-2-oxypropyl)-5-(methoxycarbonyl)-2-penten-1,5-diyl)iron. (±)-15b

The Horner–Emmons olefination of (±)-**13b** (360 mg, 0.789 mmol) with sodium hydride (1.13 mmol) in dry THF (30 mL), followed by the addition of paraformaldehyde (24 mg, 0.80 mmol) was carried out in a fashion similar to the preparation of **15a**. Purification of the residue by column chromatography (SiO$_2$, hexanes–ethyl acetate=17:3) gave (±)-**15b** (131 mg, 50%) as a yellow oil. δ_H (400 MHz, CDCl$_3$) 5.91 (1H, d, J 1.8 Hz, C=CH$_Z$), 5.51 (1H, d, J 1.8 Hz, C=CH$_E$), 4.69 (1H, t, J 7.0 Hz, H-3), 4.61 (1H, td, J 7.5, 11.6 Hz, H-4), 4.15 (1H, t, J 9.0 Hz, H-2), 3.72 (3H, s, OCH_3), 3.45 (1H, d, J 8.4 Hz, H-5exo), 2.25 (3H, s, COCH_3), 2.18 (1H, d, J 11.2 Hz, H-5endo), 0.36 (1H, d, J 8.8 Hz, H-1); δ_C (100 MHz, CDCl$_3$) 210.8, 210.1, 204.0, 180.4, 142.9, 124.0, 97.8, 62.4, 54.1, 52.0, 51.6, 40.3, 11.5. HRMS (FAB): M$_2$Na$^+$, found 523.0483. (C$_{11}$H$_{14}$O$_3$Fe)$_2$Na requires 523.0477.

4.8. Tricarbonyl(5-(methoxycarbonyl)-4-(1-methoxycarbonylethenyl)-1-(2,5-dimethoxyphenyl)-2-penten-1,5-diyl)iron (±)-16a

To a solution of (±)-**14a** (0.40 g, 0.68 mmol) in dry THF (20 mL) at −78 °C was added a solution of *n*-butyl lithium in hexanes (0.47 mL, 1.6 M, 0.75 mmol). The mixture was stirred for 1 h, and then paraformaldehyde (41 mg, 1.36 mmol) was added. The reaction mixture was warmed to room temperature over a 3 h period and then quenched with saturated aqueous NH$_4$Cl. The mixture was extracted several times with ether and the combined organic extracts were dried (Na$_2$SO$_4$), and concentrated under reduced pressure. The residue was purified by column chromatography (SiO$_2$, hexanes–ethyl acetate=4:1) to afford (±)-**16a** (0.30 g, 90%) as a yellow solid. Mp 163–166 °C (dec). [Found: C, 54.37; H, 4.66. C$_{22}$H$_{22}$O$_9$Fe requires C, 54.34; H, 4.56%]; δ_H (400 MHz, CDCl$_3$) 6.87 (1H, d, *J* 2.4 Hz, ArH), 6.86–6.77 (2H, m, ArH), 6.11 (1H, d, *J* 2.0 Hz, C=CH$_Z$), 5.45 (1H, d, *J* 2.0 Hz, C=CH$_E$), 5.41 (1H, dd, *J* 7.2, 12.4 Hz, H-4), 4.52 (1H, t, *J* 7.2 Hz, H-3), 4.42 (1H, d, *J* 12.4 Hz, H-5), 4.23 (1H, br t, *J* 8.4 Hz, H-2), 3.89, 3.76, 3.75 and 3.72 (12H total, 4×s, OCH$_3$), 0.85 (1H, d, *J* 8.8 Hz, H-1); δ_C (100 MHz, CDCl$_3$) 210.3, 209.9, 204.3, 180.4, 166.5, 153.7, 151.4, 142.6, 128.7, 124.3, 113.2, 111.6, 109.4, 93.4, 69.8, 56.1, 56.0, 55.9, 51.9, 51.6, 40.5, 10.6.

4.9. Tricarbonyl[4-(1-(dimethylphosphonyl)-6-hydroxy-2-oxohexyl)-5-methoxycarbonyl-1-(2,5-dimethoxyphenyl)-2-penten-1,5-diyl]iron. (±)-17

To a solution of (±)-**14b** (1.00 g, 1.15 mmol) in dry THF (50 mL) under N$_2$, was added a solution of TBAF in THF (2.3 mL, 1 M, 2.3 mmol). The reaction mixture was stirred at room temperature for 18 h, concentrated under reduced pressure, and the residue purified by column chromatography (SiO$_2$, ethyl acetate→ethyl acetate–methanol=4:1) to afford an equimolar mixture of diastereomers (±)-**17** as a yellow solid (0.58 g, 80%). Mp 45–47 °C; δ_H(400 MHz, CDCl$_3$) 6.88–6.77 (3H, m, ArH), 5.33 and 5.20 (1H total, 2×dd, *J*7.2, 12.8 Hz each, H-4), 4.68 and 4.64 (1H total, 2×d, *J* 12.8 Hz each, H-5), 4.32 and 4.13 (1H total, t, *J* 7.1 Hz each, H-3), 3.96–3.92 (1H, m), 3.91, 3.90, 3.76, 3.74, 3.73, 3.72, 3.69, 3.68, 3.66 (15H, 9×s, OCH$_3$), 3.60–3.56 (2H, m), 3.03 (0.5H, dd, $^3J_{HH}$ 11.7, $^2J_{PH}$ 22.0 Hz, CH(COR)P(O)(OMe)$_2$), 2.92 (0.5H, dd, $^3J_{HH}$ 11.7, $^2J_{PH}$ 21.1 Hz, CH(COR)P(O)(OMe)$_2$), 2.86–2.56 (1H, m), 2.40–2.30 (1H, m), 2.20 (1H, br s), 1.75–1.45 (4H, m), 0.74 and 0.33 (1H total, 2×d, *J* 8.4 Hz each, H-1); δ_C (100 MHz, CDCl$_3$) 210.0 [209.9], 209.4 [209.1], 204.1 (d, J_{PC} 4.7), 203.7 [203.5], 203.1 (d, J_{PC} 3.7), 179.9 [179.7], 153.6, 151.2, 128.2, 113.2, 111.5, 109.2 [109.1], 92.7 [92.6], 70.0, 61.9, 60.9, 60.6, 59.7, 56.0, 55.81, 55.77, 55.7, 55.4, 55.2, 53.3, 53.2, 53.1, 52.9, 51.4, 51.3, 45.3, 42.9, 36.9, 36.5, 31.6 [31.5], 19.5 [19.4], 12.4, 11.7 [11.6]; δ_P (162 MHz, CDCl$_3$) 21.9, 21.0. HRMS (ESI): MNa$^+$, found 647.0958. C$_{26}$H$_{33}$O$_{12}$PFeNa requires 647.0957.

4.10. Aldehyde (±)-18

To a solution of oxalyl chloride (0.13 g, 1.0 mmol) in dry CH_2Cl_2 (10 mL) at −78 °C under N_2 was added dropwise a solution of DMSO (0.14 mL, 2.0 mmol) in dry CH_2Cl_2 (10 mL). The reaction mixture was stirred for 2 min, and then a solution of (±)-**17** (0.30 g, 0.48 mmol) in dry CH_2Cl_2 (10 mL) was added dropwise over a period of 5 min. After stirring for 15 min, triethylamine (0.5 g, 5.0 mmol) was added and the reaction mixture was stirred for 5 min. The reaction mixture was warmed to room temperature over a period of 1 h, and quenched with water (50 mL). The mixture was extracted several times with CH_2Cl_2, and the combined extracts were concentrated under reduced pressure. The residue purified by column chromatography (SiO_2, ethyl acetate–methanol=10:1) to afford an equimolar mixture of diastereomers (±)-**18** (0.30 g, quant.) as a yellow solid. Mp 40–42 °C; δ_H (400 MHz, $CDCl_3$) 9.76 and 9.70 (1H total, 2×t, J 1.0 Hz each, CHO), 6.90–6.70 (m, 3H, ArH), 5.35 and 5.22 (1H total, 2×dd, J 7.2, 12.8 Hz each, H-4), 4.71 and 4.65 (1H total, 2×d, J 12.8 Hz each, H-5), 4.54 and 4.32 (1H total, 2×t, J 7.2 Hz each, H-3), 3.92, 3.91, 3.80, 3.78, 3.77, 3.75, 3.74, 3.715, 3.71, 3.70, 3.68, 3.67 (16H, 12×s and m, OCH_3 and H-2), 2.99 (0.5H, dd, $^3J_{HH}$ 11.6, $^2J_{PH}$ 22.0 Hz, CH(COR)P(O)(OMe)$_2$), 2.90 (0.5H, dd, $^3J_{HH}$ 11.6, $^2J_{PH}$ 21.2 Hz, CH(COR)P(O)(OMe)$_2$), 2.82 (0.5H, t, J 7.0 Hz), 2.77 (0.5H, t, J 7.2 Hz), 2.52–2.34 (3H, m), 1.95–1.75 (2H, m), 0.77 and 0.32 (1H total, 2×d, J 8.4 Hz, H-1); δ_P (162 MHz, $CDCl_3$) 21.7, 20.8. HRMS (ESI): MNa$^+$, found 645.0811. $C_{26}H_{31}O_{12}PFeNa$ requires 645.0801. Due to the presence of two diastereomers, as well as ^{31}P coupling, interpretation of the ^{13}C NMR spectrum was not attempted.

4.11. Tricarbonyl(5-(methoxycarbonyl)-4-(6-oxo-1-cyclohexenyl)-1-(2,5-dimethoxyphenyl)-2-penten-1,5-diyl)iron. (±)-19

To a suspension of NaH (8 mg, 0.3 mmol) in dry THF (10 mL) at 0 °C under N_2 was added dropwise a solution of (±)-**18** (0.10 g, 0.16 mmol) in dry THF (10 mL). The reaction mixture was stirred for 5 h, warmed to room temperature, and then heated at reflux for 4 h. After cooling to room temperature, the reaction mixture was quenched with saturated NH_4Cl (20 mL) and the resulting mixture was extracted several times with CH_2Cl_2. The combined extracts were concentrated under reduced pressure, and the residue purified by column chromatography (SiO_2, hexanes–ethyl acetate=1:1) to afford (±)-**19** (40 mg, 50%) as a bright yellow solid. Mp 160–162 °C; δ_H (400 MHz, $CDCl_3$) 6.85–6.75 (3H, m, ArH), 6.49 (1H, br s, H-3'), 5.29 (1H, dd, J 7.0, 12.2 Hz, H-4), 4.63 (1H, t, J 7.6 Hz, H-3), 4.36 (1H, d, J 12.8 Hz, H-5), 4.20 (1H, br t, J 8.4 Hz, H-2), 3.90, 3.74, 3.73 (9H, 3×s, OCH_3), 2.36–2.25 (4H, m), 1.89–1.84 (2H, m), 0.86 (1H, d, J 8.8 Hz, H-1); δ_C (100 MHz, $CDCl_3$) 210.6, 210.1, 204.4, 198.4, 180.6, 153.7, 151.4, 143.9, 141.8, 129.1, 113.0, 111.6, 109.3, 93.1, 69.4, 58.3, 56.0, 55.9, 51.6, 39.3, 38.9, 25.9, 22.7, 9.7. HRMS (ESI): MNa$^+$, found 519.0712. $C_{24}H_{24}O_8FeNa$ requires 519.0718.

4.12. Carvonic acid methyl ester (±)-23a

To a solution of the anion generated from trimethyl phosphonoacetate (0.533 g, 2.73 mmol) and NaH (262.3 mg, 5.460 mmol) in dry THF (50 mL) at 0 °C, was added solid cation **20** (1.0 g, 2.7 mmol) in one portion. The reaction mixture warmed to room temperature and stirred for 2 h, during this time a yellow-brown turbidity began to appear. The reaction mixture was diluted CH_2Cl_2 (50 mL), saturated solution of methanolic $NaHCO_3$ (80 mL) was added, and the mixture stirred overnight. Water (30 mL) was added, and the mixture extracted several times with CH_2Cl_2. The combined extracts were dried ($MgSO_4$) and concentrated. The residue was purified by flash column chromatography (SiO_2, ethyl acetate–hexanes=50%→70% gradient) to afford a mixture of diastereomeric cyclohexenones **21a/22a** as a light yellow oil (458 mg, 87%). Due to the complex nature of the ^1H and ^{13}C NMR spectra, this mixture was not further characterized. The mixture of diastereomeric phosphonate esters (210 mg, 0.721 mmol) was added to a suspension of sodium hydride (43 mg, 1.1 mmol) in dry THF (20 mL) at 0 °C. The mixture was stirred at 0 °C for 30 min. Paraformaldehyde (43.4 mg, 1.48 mmol) was added slowly at a rate such that the temperature remained below 30 °C, and the mixture was stirred for 1 h. The mixture was diluted with H_2O and extracted several times with CH_2Cl_2. The combined extracts were dried ($MgSO_4$) and concentrated. The residue was purified by flash chromatography (SiO_2, ether–hexanes=0%→75% gradient) to afford a mixture of (±)-**23a** and (±)-**24a** (10:1 ratio by ^1H NMR integration) as a pale oil (136 mg, 97%). Careful column chromatography gave a pure sample of **23a**. v_{max} (CH_2Cl_2) 3470, 2924, 2853, 1717, 1675, 1457, 1375 cm^{-1}; δ_H (400 MHz, CDCl$_3$) 6.76–6.72 (1H, m, H-3), 6.27 (1H, s, C=CH$_2$), 5.58 (1H, s, C=CH$_2$), 3.74 (3H, s, OCH$_3$), 3.29–3.20 (1H, m), 2.62 (1H, ddd, J 2.4, 4.0, 16.2 Hz, H-6), 2.62–2.53 (1H, m), 2.44 (1H, dd, J 12.8, 16.0 Hz, H-6), 2.35–2.25 (1H, m), 1.79 (3H, s, 2-Me); δ_C (100 MHz, CDCl$_3$) 199.2, 167.0, 144.4, 142.4, 135.7, 124.8, 52.2, 43.1, 37.0, 31.9, 15.9. HRMS (ESI): MNa$^+$, found 411.1786. $(C_{11}H_{14}O_3)_2Na$ requires 411.1778.

4.13. Diethyl (1-(4-methyl-3-oxocyclohex-4-en-1-yl)-2-oxopropyl)phosphonate (±)-21b and diethyl (1-(2-methyl-3-oxocyclohex-4-en-1-yl)-2-oxopropyl)phosphonate (±)-22b

To an ice cold stirring suspension of NaH (25 mg, 0.62 mmol) in freshly distilled THF (10 mL) was added dropwise diethyl 2-oxopropylphosphonate (79 mg, 0.41 mmol) in drops. The resultant mixture was stirred at 0 °C for 45 min. The solid cation **20** (150 mg, 0.409 mmol) was added slowly. The reaction mixture was stirred at room temperature for 2 h. The reaction mixture was diluted with CH_2Cl_2 (10 mL) and saturated $NaHCO_3$/MeOH (10 mL). The reaction was stirred for 24 h. The reaction was quenched with water (10 mL). The organic portions were extracted several times with CH_2Cl_2, washed with brine, dried (Na_2SO_4) and concentrated. Purification of the residue by flash column chromatography (SiO_2, ethyl acetate–hexane=0–60% gradient) afforded an inseparable mixture of regioisomeric

cyclohexenones (±)-**21b** and (±)-**22b** (~7:1 ratio by ^{1}H NMR integration) as a colorless oil (89.7 mg, 74%). ^{1}H NMR (CDCl$_3$, major isomer, 300 MHz) δ 6.75–6.62 (1H, m, H-3), 4.18–4.07 (4H, m, P(O)(OC*H$_2$*CH$_3$)$_2$), 3.22 and 3.15 (1H total, 2×dd, *J* 8.7, 9.3 Hz each, C*H*(COMe)P(O)(OEt)$_2$), 2.89–2.66 (2H, m), 2.43–2.21 (3H, m), 2.33 and 2.29 (3H total, 2×s, C(O)*Me*), 1.75 (3H, s, Me-2), 1.32 (6H total, t, *J* 7.2 Hz, OCH$_2$C*H$_3$*); ESI-HRMS *m/z* 325.1175 (calcd for C$_{14}$H$_{23}$O$_5$PNa (M+Na) *m/z* 325.1175). Due to the presence of two diastereomers, as well as ^{31}P coupling, interpretation of the ^{13}C NMR spectrum was not attempted.

4.14. 2-Methyl-5-(1-methylene-2-oxopropyl)-2-cyclohexenone (±)-23b and 6-methyl-5-(1-methylene-2-oxopropyl)-2-cyclohexenone (±)-24b

The Horner–Wadsworth–Emmons olefination of **21b/22b** (74 mg, 0.25 mmol) with paraformaldehyde (14 mg, 0.47 mmol) was carried out in a fashion similar to the preparation of **23a/24a**. The residue was purified by flash column chromatography (SiO$_2$, ethyl acetate–hexane: 0–60% gradient) to afford an inseparable mixture of regioisomers (±)-**23b** and (±)-**24b** (~5:1 by ^{1}H NMR integration) as a pale oil (39 mg, 89%). **23b**: δ_H (300 MHz, CDCl$_3$) 6.75–6.69 (1H, m, H-3), 6.14 (1H, C$=$C*H$_2$*), 6.01 (1H, s, C$=$C*H$_2$*), 3.42–3.28 (1H, H-5), 2.58–2.42 (2H, m, H-6 & H-6'), 2.41–2.30 (4H, m & s, MeCO & H-4), 2.26–2.12 (1H, m, H-4'), 1.78 (3H, s, Me-2); δ_C (75 MHz, CDCl$_3$) 199.5, 199.3, 150.7, 144.6, 135.6, 125.2, 43.1, 35.4, 32.1, 26.6, 15.9. **24b**: δ_H (300 MHz, CDCl$_3$, partial) 6.93–6.84 (m), 6.20 (s), 6.05–5.98 (m), 6.87 (s), 3.13–2.99 (m), 2.72–2.60 (m). HRMS (ESI): MNa$^+$, found 201.0886. C$_{11}$H$_{14}$O$_2$Na requires 201.0887.

4.15. 2-Methyl-5-(1-phenylsulfonylethenyl)-2-cyclohexenone (±)-23c

To an ice cold stirring suspension of NaH (25 mg, 0.62 mmol) in freshly distilled THF (10 mL) was added dropwise diethyl (phenylsulfonyl)methylphosphonate (116 mg, 0.409 mmol). The resultant mixture was stirred at 0 °C for 45 min. The solid cation **20** (150 mg, 0.409 mmol) was added slowly. The reaction mixture was stirred at room temperature for 2 h. The reaction mixture was diluted with CH$_2$Cl$_2$ (10 mL) and saturated NaHCO$_3$/MeOH (10 mL). The reaction was stirred for 24 h. The reaction was quenched with water (10 mL). The organic portions were extracted several times with CH$_2$Cl$_2$, washed with brine, dried (Na$_2$SO$_4$) and concentrated. Purification of the residue by flash column chromatography (SiO$_2$, ethyl acetate–hexane=0–80% gradient) afforded **21c** as a pale oil (76 mg, 47%). HRMS (ESI): MNa$^+$, found 423.1002. C$_{18}$H$_{25}$O$_6$SPNa requires 423.1002. This compound was used in the olefination reaction without further characterization. To an ice-cold stirring suspension of NaH (6 mg, 0.2 mmol) in dry THF (3 mL) was added **21c** (50 mg, 0.13 mmol). The mixture was stirred at 0 °C for 30 min, paraformaldehyde (14 mg, 0.47 mmol) was added slowly at such a rate that the temperature remained below 30 °C and the reaction mixture stirred for 1 h at room temperature. The reaction

mixture was diluted H_2O (10 mL) and the mixture extracted several times with CH_2Cl_2. The combined extracts were dried ($MgSO_4$) and concentrated. The residue was purified by flash column chromatography (SiO_2, ethyl acetate–hexane=0–45% gradient) to afford (±)-**23c** (25 mg, 72%) as a pale oil. δ_H (300 MHz, $CDCl_3$) 7.85 (2H, d, J 7.7 Hz, ArH), 7.65 (1H, t, J 8.3 Hz, ArH), 7.55 (2H, t, J 7.7 Hz, ArH), 6.66 (1H, d, J 5.8 Hz, H-3), 6.53 (1H, s, C=CH_2), 5.89 (1H, s, C=CH_2), 3.08–2.95 (1H, m), 2.67–2.55 (1H, m), 2.43–2.23 (3H, s & m), 1.74 (3H, s, Me-2); δ_C (75 MHz, $CDCl_3$) 197.8, 153.1, 143.8, 138.9, 135.8, 134.1, 129.7, 128.3, 124.5, 43.6, 35.6, 33.0, 15.9. HRMS (ESI): MNa⁺, found 299.0712. $C_{15}H_{16}O_3SNa$ requires 299.0709.

4.16. 10-Hydroxycarvone (±)-25

To a stirring solution of LDA in heptanes (0.91 mL, 2.0 M, 1.8 mmol) in THF (5 mL) at −78 °C was added dropwise a solution of **23a** (91 mg, 0.61 mmol) in THF (1 mL). The reaction mixture was stirred at this temperature for 30 min after which a solution of DIBAL–H in hexanes (2.8 mL, 1.0 M, 2.8 mmol) was slowly added. The reaction mixture was stirred at −78 °C for 3 h, after which the mixture was warmed to room temperature and stirred for 1 h. The reaction was quenched with water, extracted several times with CH_2Cl_2, and the combined extracts were washed with brine and concentrated. The residue was purified by flash column chromatography (SiO_2, acetone–hexanes=0%→35% gradient) to afford (±)-**25** (56 mg, 76%) as a yellow oil. δ_H(300 MHz, CD_3OD) 6.92–6.85 (1H, m, H-3), 5.14 (1H, s, C=CH_2), 4.96 (1H, s, C=CH_2), 4.08 (2H, s, CH_2OH), 2.88–2.76 (1H, m), 2.62–2.35 (4H, m), 1.76 (3H, br s, Me-2); δ_H (75 MHz, $CDCl_3$) 199.7, 150.4, 144.6, 135.8, 110.6, 65.1, 43.5, 38.5, 31.8, 15.9. The NMR spectral data for this product was consistent with the literature values.[14a]

4.17. Carvonic acid (±)-26

To a solution of (±)-**23a** (69 mg, 0.46 mmol) in THF/methanol/H_2O (2:2:1, 4 mL) was added in small portions lithium hydroxide (116 mg, 2.77 mmol). The mixture was stirred at room temperature for 1 h and then the mixture was acidified with dilute aqueous HCl and the resulting mixture was extracted several times with ethyl acetate. The combined extracts were washed with brine, dried ($NaSO_4$) and concentrated. The residue was purified by flash chromatography (SiO_2, acetone–hexanes=0%→50% gradient) to afford carvonic acid (±)-**26** (43 mg, 52%) as a yellowish oil. δ_H (300 MHz, $CDCl_3$) 6.80–6.72 (1H, m, H-2), 6.44 (1H, s, C=CH_2), 5.72 (1H, s, C=CH_2), 3.32–3.20 (1H, m, H-5), 2.66 (1H, dd, J 2.8, 11.8 Hz, H-6), 2.62–2.57 (1H, m), 2.48 (1H, dd, J 9.6, 12.3 Hz, H-6'), 2.40–2.29 (1H, m), 1.80 (3H, s, Me-2); δ_C($CDCl_3$, 75 MHz) 199.2, 144.4, 141.8, 135.8, 127.2, 43.1, 36.8, 31.8, 15.9, signal for COOH not observed. The NMR spectral data for this product was consistent with the literature values.[13b]

Acknowledgments

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9All compounds are racemic mixtures of enantiomers. Only one enantiomer has been pictured for clarity.

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Electronic Supporting Information

Reactivity of acyclic (pentadienyl)iron(1+) cations with phosphonate stabilized nucleophiles: Application to the synthesis of oxygenated metabolites of carvone

Do W. Lee, Charles F. Manful, Jayapal Reddy Gone, Yuzhi Ma, and William A. Donaldson*

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-13a

16.23

2.49

2.31

1.00

7 6 5 4 3 2 1 0 PPM

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^{13}C NMR
(100 MHz, CDCl$_3$)

($\pm$) - 13a

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-13b

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O P(OEt)$_2$
H
Me(O)C
MeO$_2$C Fe(CO)$_3$

^{13}C NMR
(100 MHz, CDCl$_3$)

(±) - 13b

200   150   100   50   PPM

S5

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-14a

2.94

1.00   1.01   1.05

8.89

1.00

1.13

7   6   5   4   3   2   1   PPM

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)-14a

| F1: 100.526 | F2: 399.745 | SW1: 24510 | | OF1: 10565.2 | | PTS1d: 31875 , 32768 |
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OTBDPS

P(O)(OMe)$_2$

O

MeO$_2$C

Fe
(CO)$_3$

OMe

OMe

^{1}H NMR
(400 MHz, CDCl$_3$)

(±) - 14b

20.19

10.54

6.30

5.49

4.23

3.17

2.42

2.00

1.15

1.00

0.93

7   6   5   4   3   2   1   PPM

S8

¹³C NMR
(100 MHz, CDCl₃)

(±) - 146

Structure labels: OTBDPS, MeO₂C, O, P(O)(OMe)₂, Fe, (CO)₃, OMe, OMe

Peak list (ppm):
- 210.240
- 209.582
- 204.073
- 204.018
- 203.769
- 179.937
- 179.908
- 153.749
- 151.349
- 135.702
- 134.104
- 134.054
- 129.720
- 129.693
- 128.453
- 128.416
- 127.770
- 113.407
- 111.648
- 109.485
- 109.384
- 92.840
- 92.749
- 77.547
- 77.230
- 76.911
- 70.078
- 70.003
- 63.708
- 63.613
- 61.280
- 60.060
- 55.978
- 55.923
- 55.876
- 55.727
- 55.537
- 53.678
- 53.609
- 53.263
- 53.195
- 51.626
- 51.509
- 45.423
- 43.208
- 36.765
- 36.734
- 31.872
- 26.991
- 19.823
- 19.348
- 12.742

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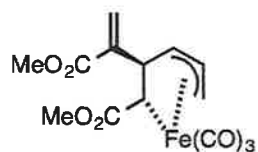
(S)

MeO$_2$C

MeO$_2$C

Fe(CO)$_3$

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-15a
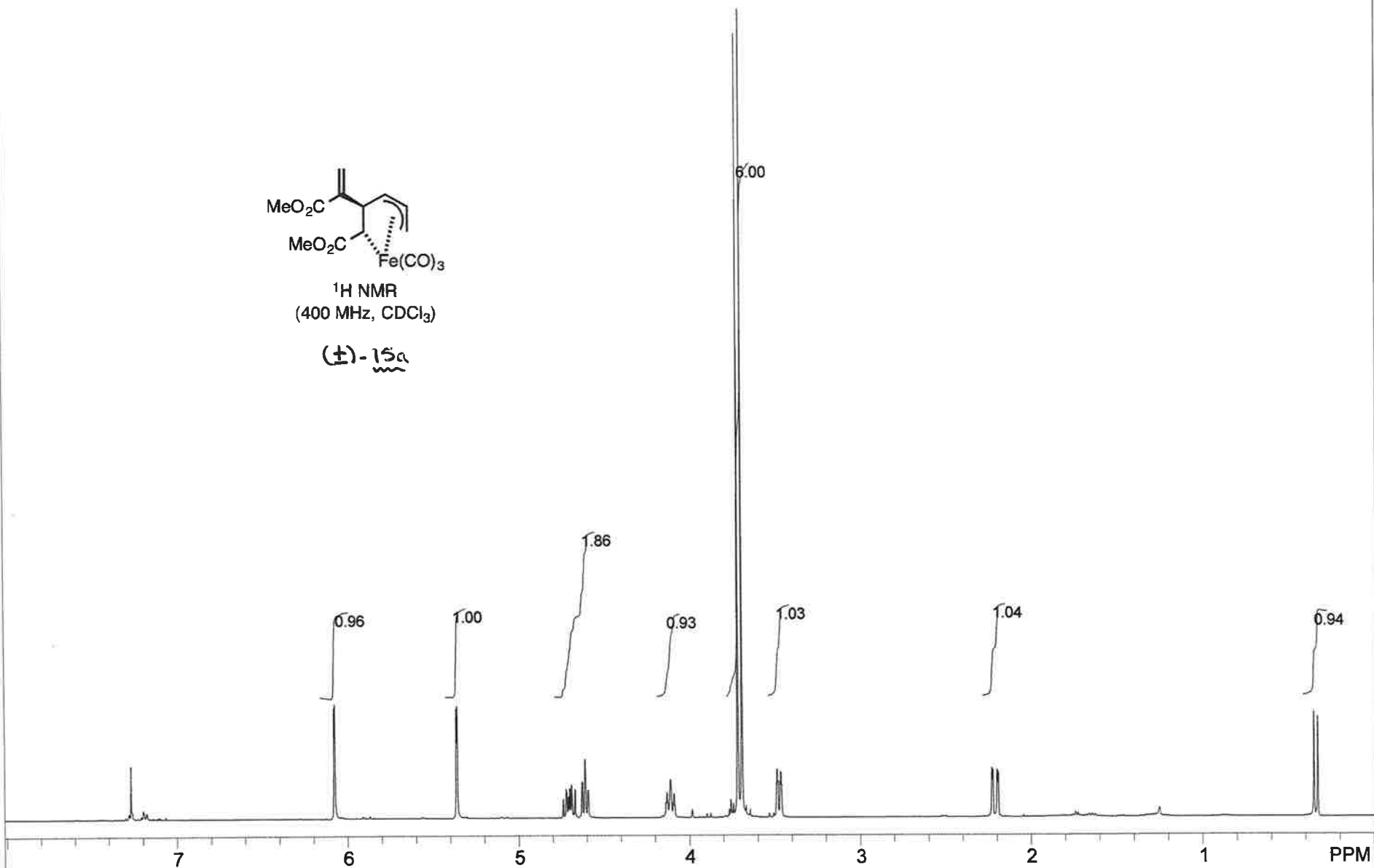
6.00

1.86

0.96

1.00

0.93

1.03

1.04

0.94

7   6   5   4   3   2   1   PPM

S10

^{13}C NMR
(100 MHz, CDCl$_3$)

(±) - 15a
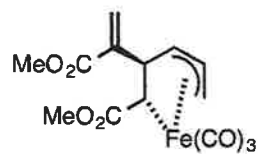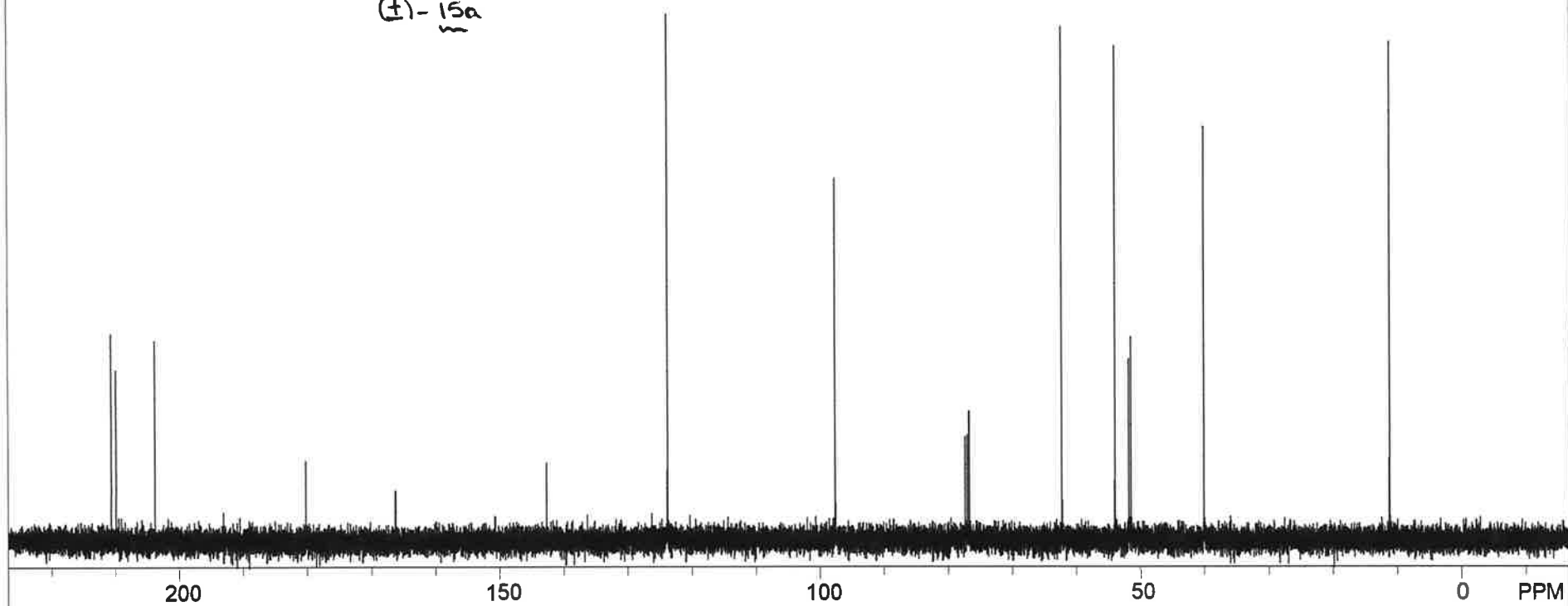
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H$_3$C — O

MeO$_2$C

Fe(CO)$_3$

^{1}H NMR
(400 MHz, CDCl$_3$)

(±) - 15b

Peak	Integration
3.00	
2.90	
1.96	
1.17	
1.10	
1.14	
1.05	
1.07	
0.98	

S12

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)-15b

210.934
210.214
204.075
198.706
180.364
151.395
124.209
97.391
77.545
77.433
77.230
76.913
63.893
53.987
51.679
39.751
26.828
10.853

200   150   100   50   PPM

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-16a

7.09

1.00

2.01

0.00

1.00 1.02 0.95

2.82

1.05

7   6   5   4   3   2   1   PPM

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USER: -- DATE: Aug 25 2010

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)-16a

Peak labels: 210.337, 209.948, 204.323, 180.432, 166.472, 153.696, 151.424, 142.558, 128.735, 124.307, 113.151, 111.608, 109.365, 93.354, 77.551, 77.230, 76.908, 69.809, 56.097, 55.973, 55.877, 51.931, 51.555, 40.481, 10.642

200   150   100   50   PPM
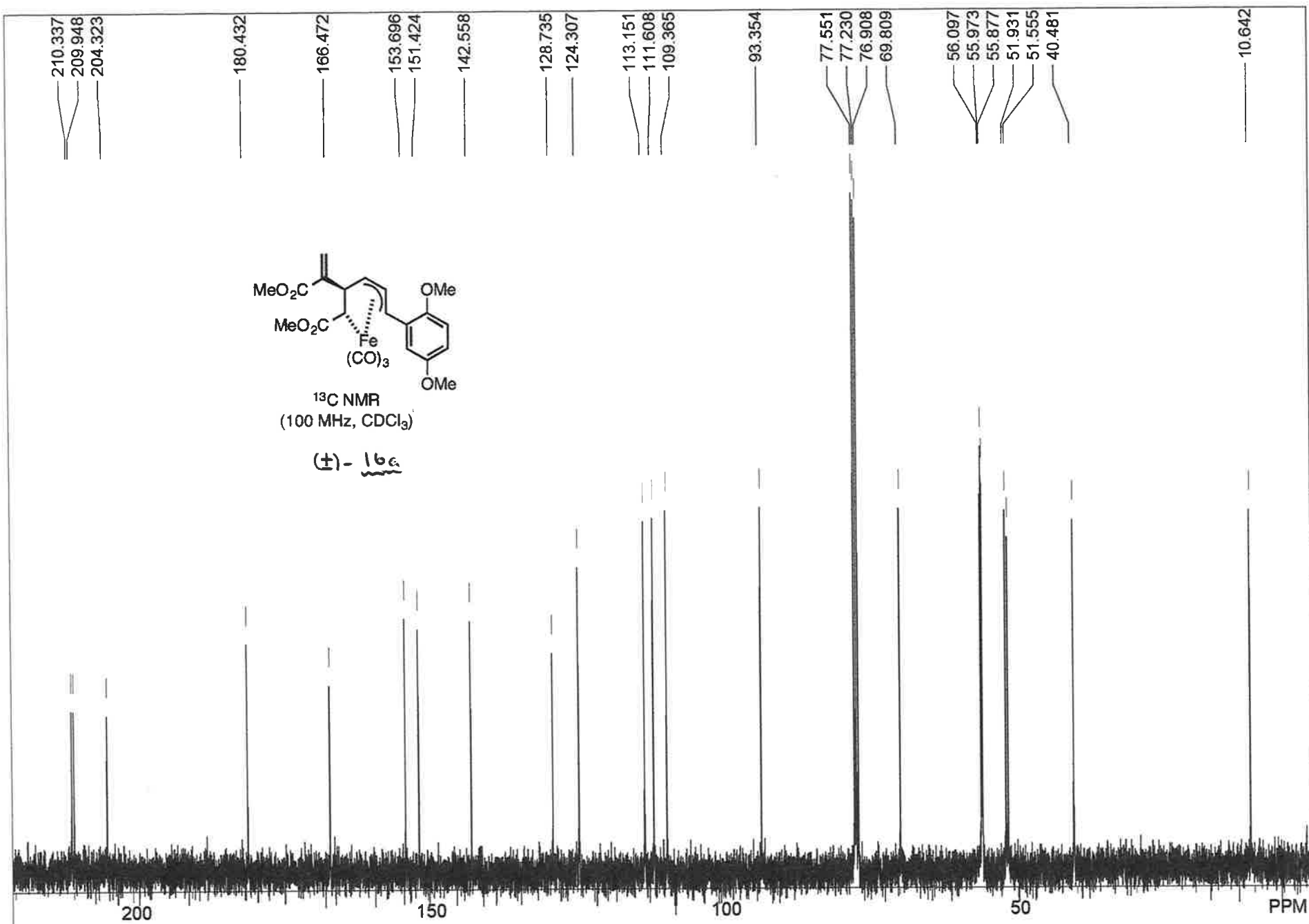
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OH

P(O)(OMe)$_2$

OMe

MeO$_2$C

O

Fe
(CO)$_3$

OMe

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-17

2.77

0.92   0.91   1.00   17.37   1.04   1.10   1.03   1.32   4.98   2.48

7   6   5   4   3   2   1   PPM

OH

P(O)(OMe)$_2$

OMe

MeO$_2$C

O

Fe
(CO)$_3$

OMe

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)- 17

200   150   100   50   PPM

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USER: -- DATE: Oct 20 2010

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S 17

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-18

Peaks labeled: 0.82, 3.00, 1.01, 1.98, 15.83, 2.43, 2.88, 2.31, 1.03

Axis: 10, 8, 6, 4, 2, PPM

S 18

P(O)(OMe)$_2$

OMe

MeO$_2$C

Fe
(CO)$_3$

OMe

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)-18

200	150	100	50	PPM

F1: 100.526	F2: 399.745	SW1: 24510		OF1: 10562.8		PTS1d: 31875	32768
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^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-19

3.03

0.95

0.96

0.95 0.98 0.93

6/18

3/00

4.03

2.17

1.02

7   6   5   4   3   2   1   PPM
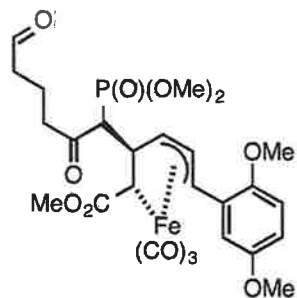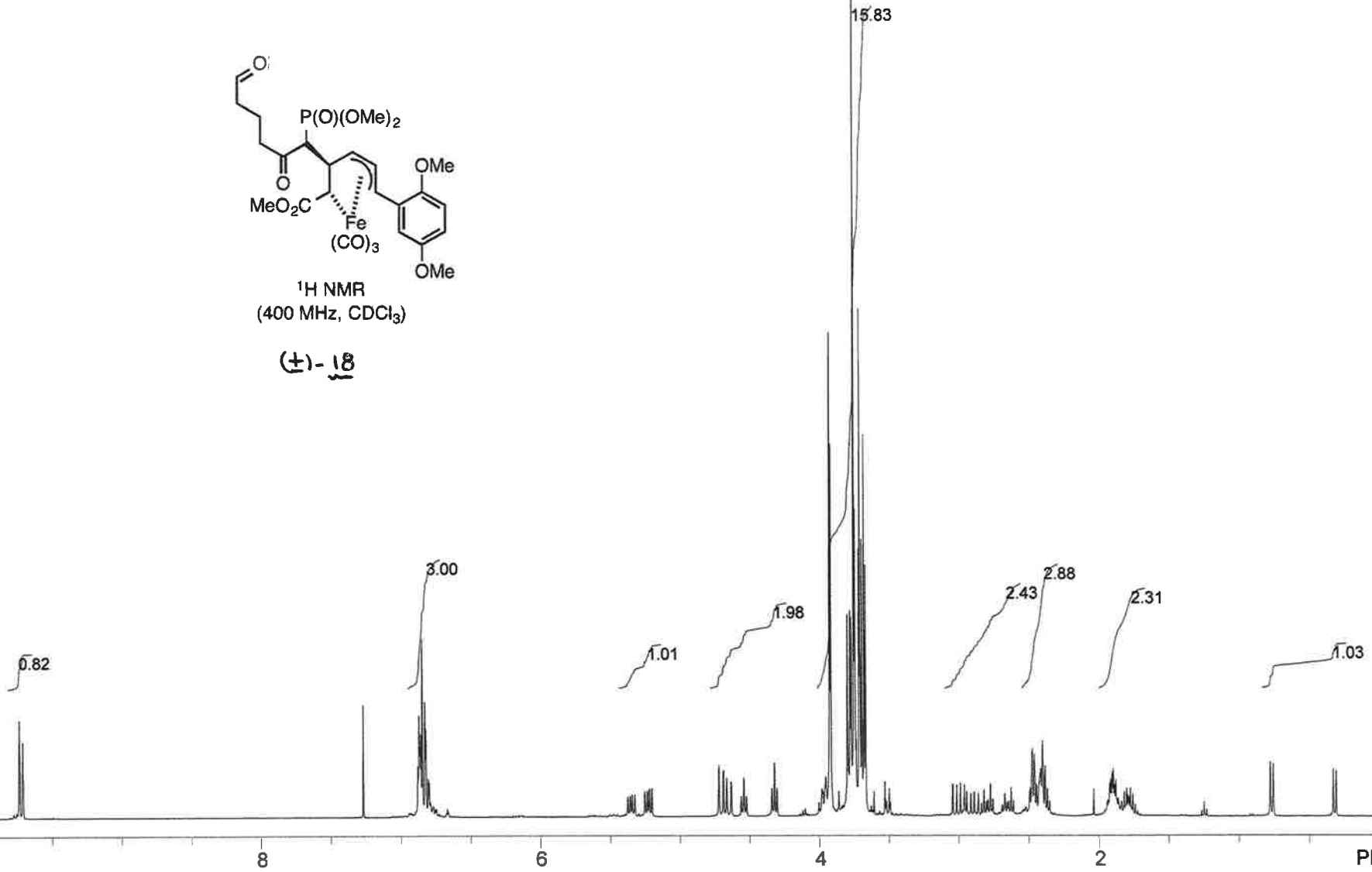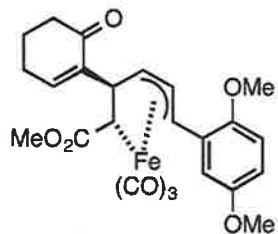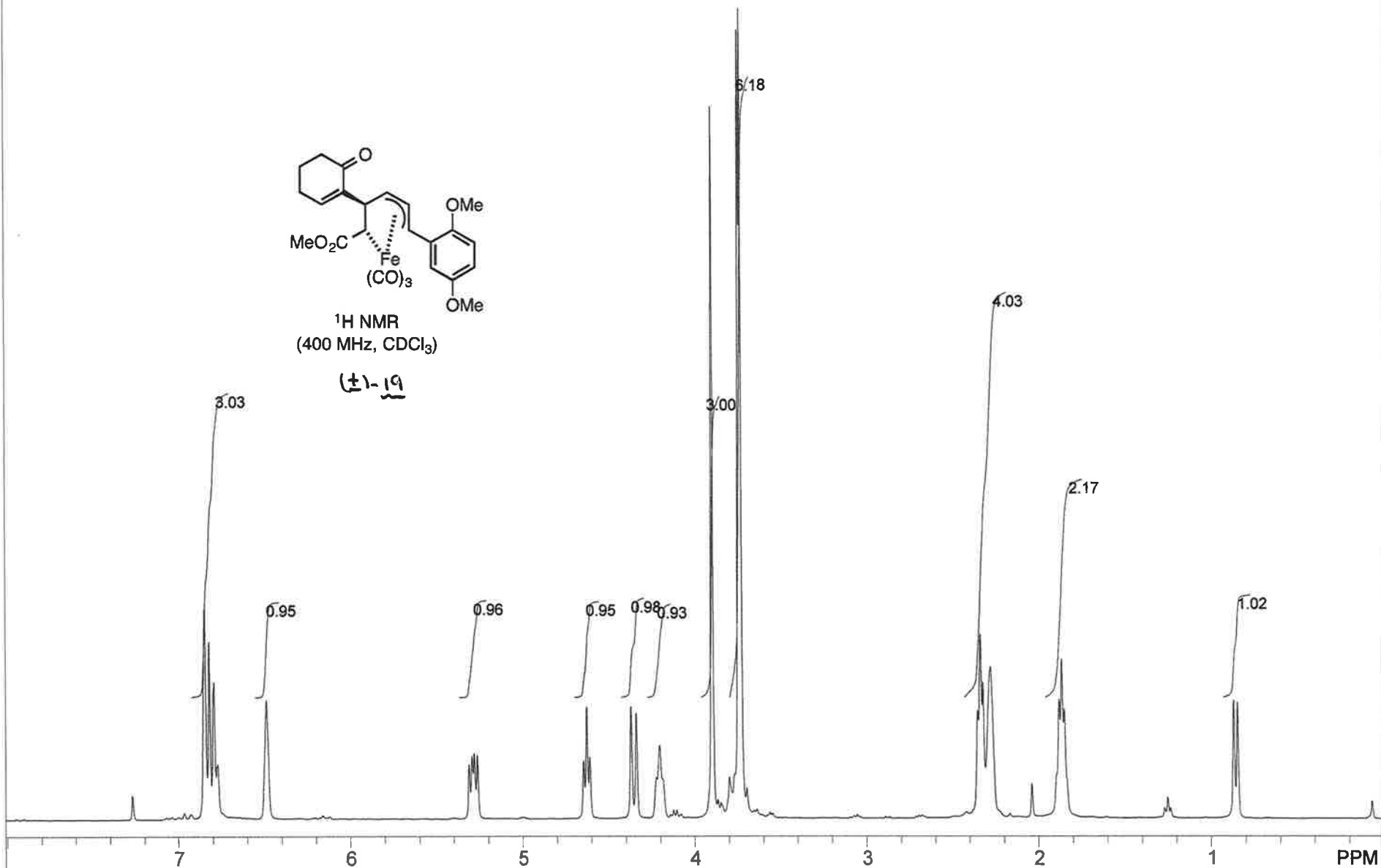
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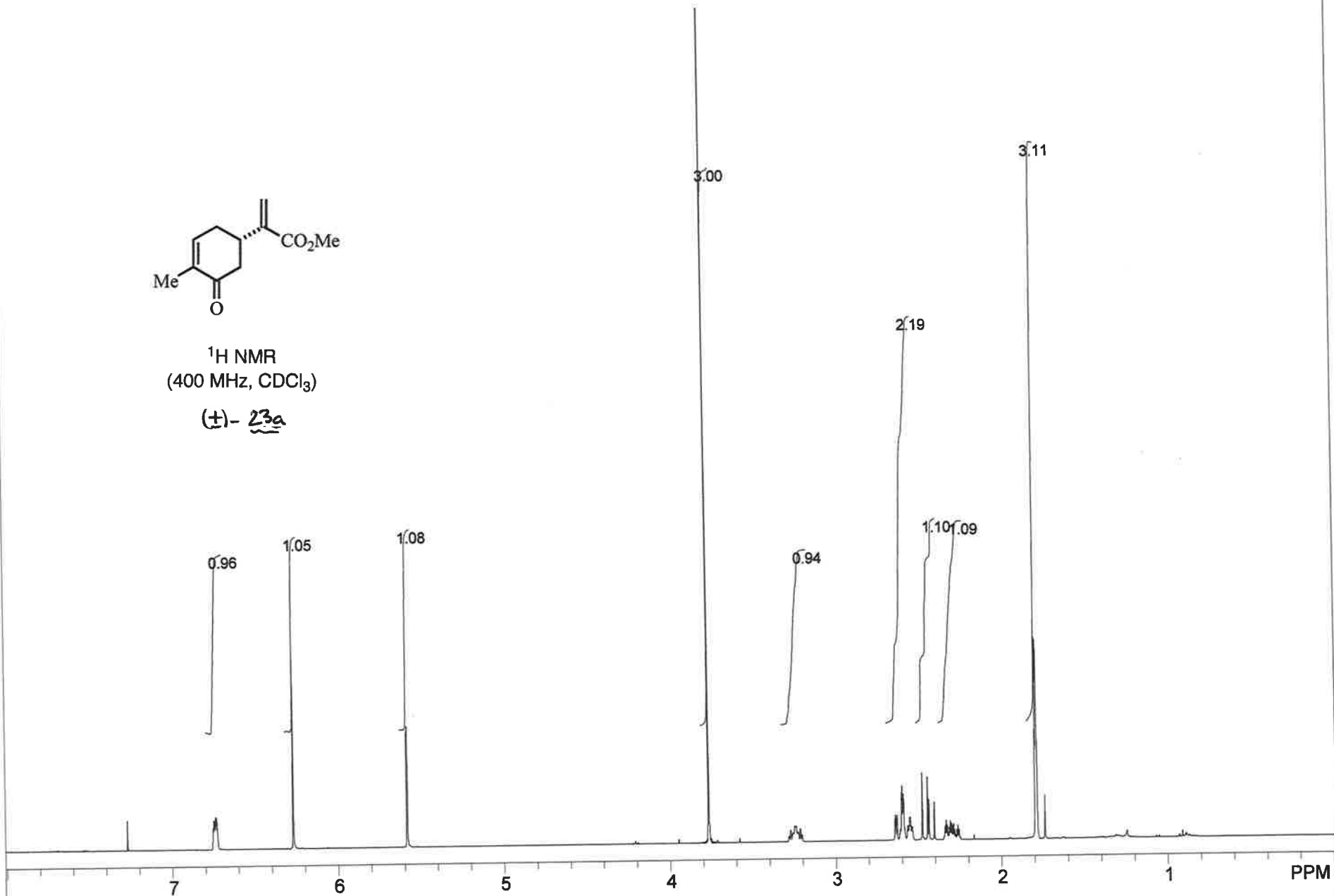
S 20

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)-19

Peak labels (ppm): 210.612, 210.103, 204.407, 198.399, 180.598, 153.718, 151.398, 143.945, 141.762, 129.143, 113.031, 111.598, 109.286, 93.056, 77.549, 77.230, 76.906, 69.397, 58.273, 56.009, 55.924, 51.573, 39.298, 38.911, 25.856, 22.685, 9.650

X-axis: 200, 150, 100, 50, PPM

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)- 23a

3.00

3.11

2.19

1.10 1.09

0.96

1.05

1.08

0.94

7   6   5   4   3   2   1   PPM

S 22

^{13}C NMR
(100 MHz, CDCl$_3$)

(±)- 23a

Peak labels (left to right): 199.173, 166.999, 144.405, 142.432, 135.669, 124.809, 77.542, 77.230, 76.914, 52.195, 43.113, 36.995, 31.854, 15.873

x-axis: 200, 150, 100, 50, PPM

(major) ^{1}H NMR   (minor)
(300 MHz, CDCl$_3$)

21b   22b

Me

Me

Me

Me

O

O

O

O

(major) ¹H NMR (minor)
(300 MHz, CDCl₃)

23b   24b

0.92

0.99

1.00

7.08

3.01

1.10

0.87

0.56

0.18

0.19 0.16 0.19

0.15

7   6   5   4   3   2   1   PPM

S 25

199.441
199.198
150.707
148.455
144.632
135.625
129.189
127.177
125.184
77.653
77.431
77.230
76.807
45.166
43.051
42.845
35.327
32.288
32.086
26.594
26.508
15.904
13.068

(major) 23b

(minor) 24b

^{13}C NMR
(75 MHz, CDCl$_3$)

200   150   100   50   PPM

USER: -- DATE: May 31 2011

13C OBSERVE;blank line

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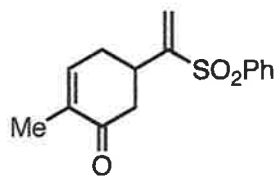
^{1}H NMR
(300 MHz, CDCl$_3$)

(±) - 23c
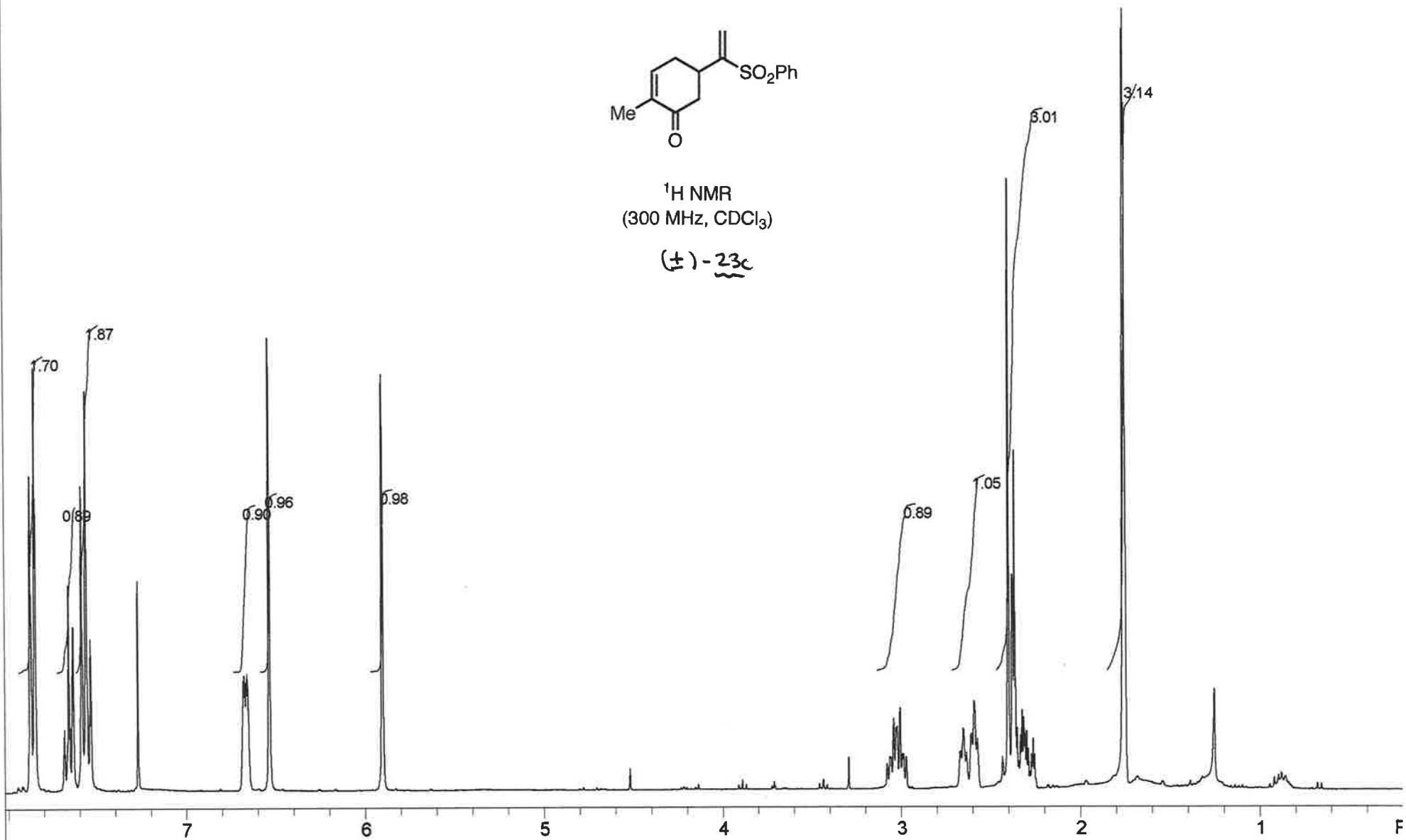
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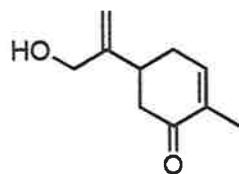| F1: 300.133 | F2: 75.476 | SW1: 4803 | | OF1: 1803.8 | | PTS1d: 9596 , 16384 | USER: -- DATE: Jul 30 20 |
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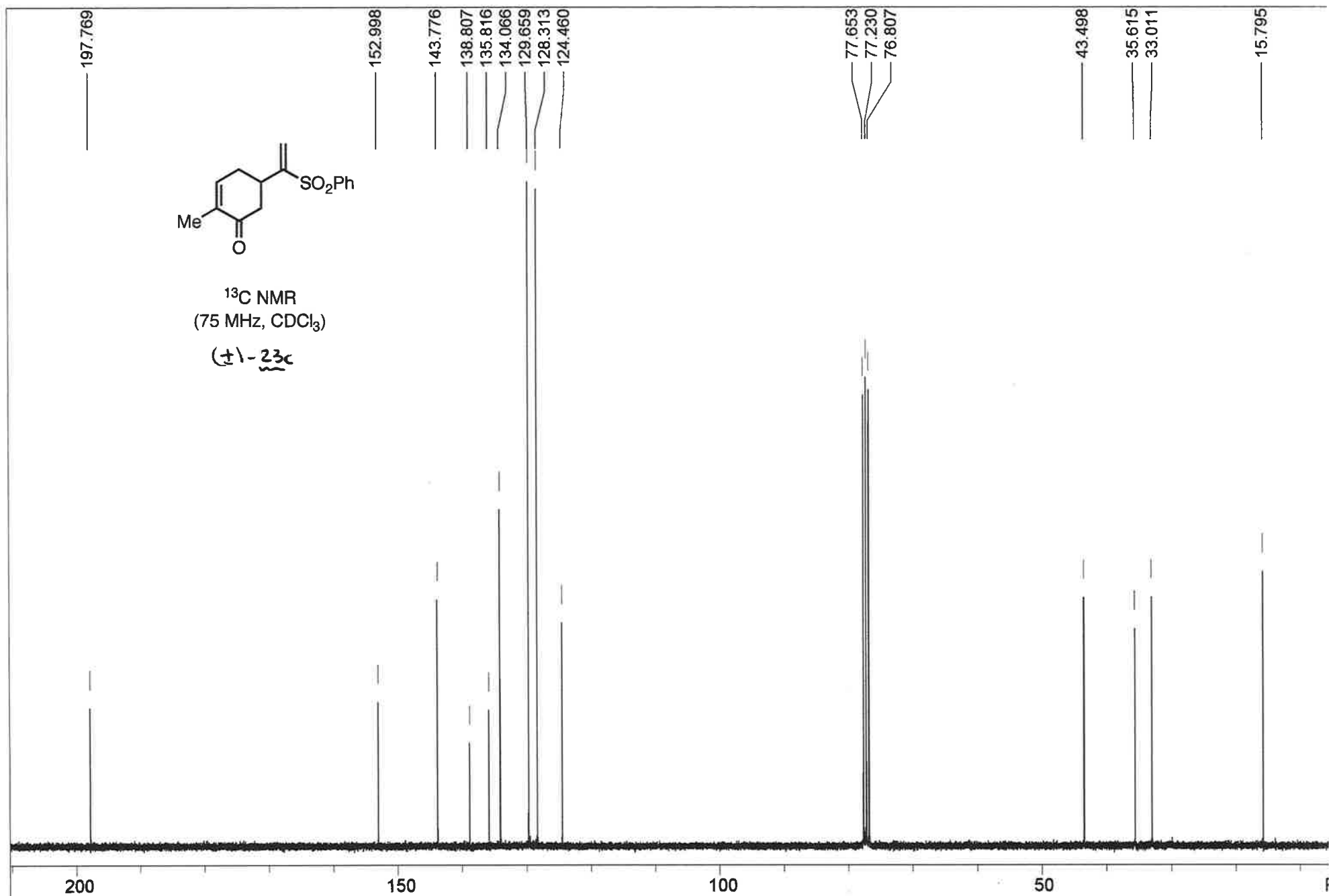
^{13}C NMR
(75 MHz, CDCl$_3$)

(±)-23c

Peak labels (ppm): 197.769, 152.998, 143.776, 138.807, 135.816, 134.066, 129.659, 128.313, 124.460, 77.653, 77.230, 76.807, 43.498, 35.615, 33.011, 15.795

^{1}H NMR
(300 MHz, CD$_3$OD)

(±)-25
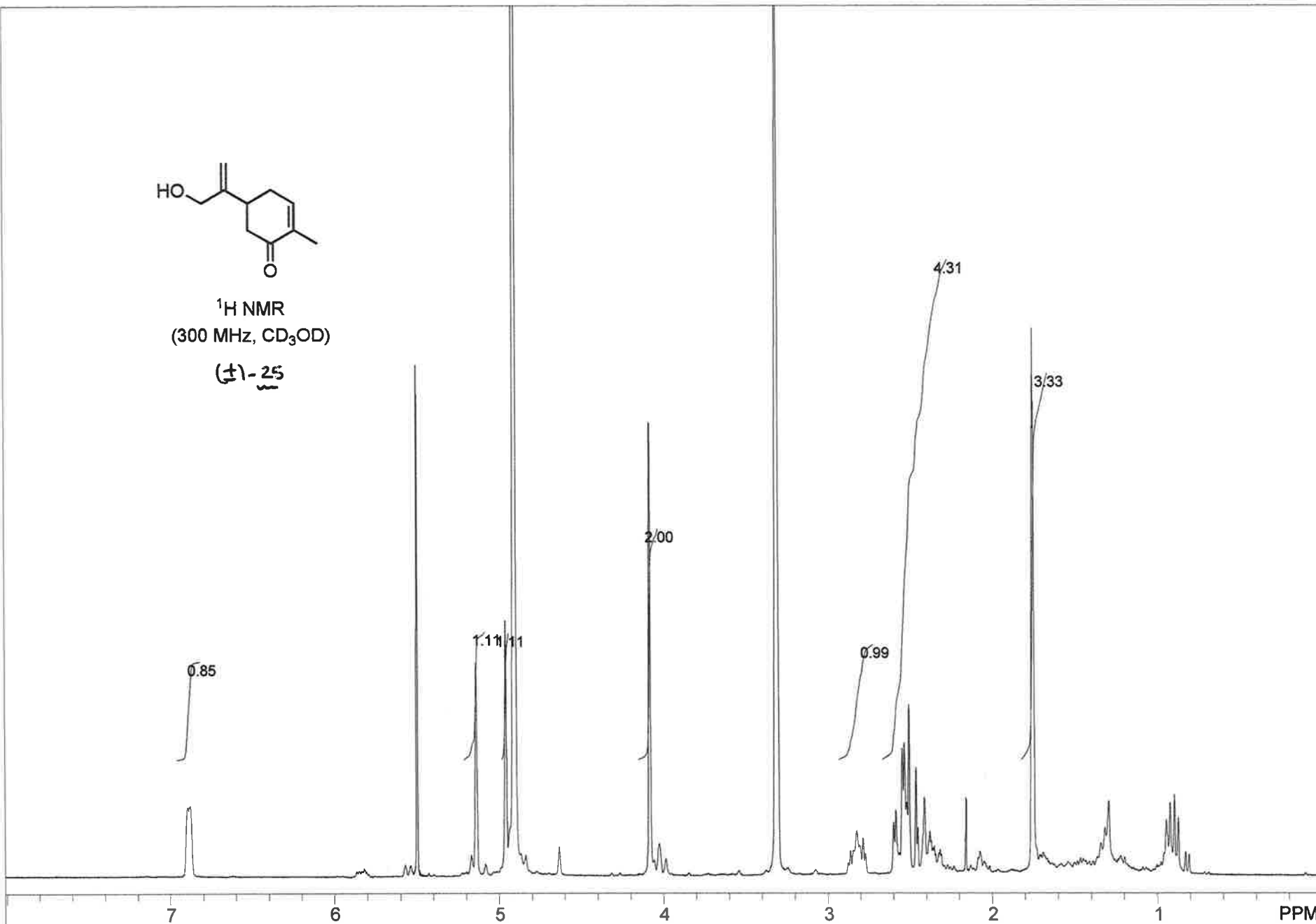
STANDARD 1H OBSERVE;blank line

F1: 300.134	F2: 75.476	SW1: 4803		OF1: 1804.1		PTS1d: 9596 , 16384
EX: s2pul		PW: 6.2 us	PD: 1.0 sec	NA: 208	LB: 0.0	Nuts - $EA387-re-f1p.fid

USER: -- DATE: Apr 27 2012

S 29

^{13}C NMR
(75 MHz, CDCl$_3$)

(±)-25

199.664

150.445
144.641
135.761

110.626

77.653
77.230
76.806

65.074

43.463
38.458
31.817

15.923

200   150   100   50   PPM

^{1}H NMR
(400 MHz, CDCl$_3$)

(±)-26

| 0.91 | 1.03 | 1.03 | 0.97 | 2.04 | 1.12 | 1.06 | 3.00 |

0.00

S 31

^{13}C NMR
(75 MHz, CDCl$_3$)

(±)-26

199.165
144.395
141.771
135.790
127.160
77.654
77.431
77.230
76.806
43.056
36.789
31.801
31.165
15.906

200   150   100   50   PPM

13C OBSERVE;blank line

| F1: 75.476 | F2: 300.133 | SW1: 18868 | | OF1: 8300.2 | | PTS1d: 34246 , 65536 | |
| EX: s2pul | | PW: 7.3 us | PD: 1.0 sec | NA: 20544 | LB: 2.0 | | Nuts - $EA313-re-re-f14C.fid |