Electronic Supplementary Material (ESI) for Organic & Biomolecular Chemistry.

Supporting Information

Reactions of benzyltriphenylphosphonium salts under photoredox catalysis

Andrew M. Boldt,[‡a] Sidney I. Dickinson,[‡a] Jonathan R. Ramirez,[a] Anna M. Benz-Weeden,[a] David S. Wilson,[a] and Susan M. Stevenson*[a]

[a]*Department of Chemistry, Carthage College, Kenosha, WI 53140 USA*

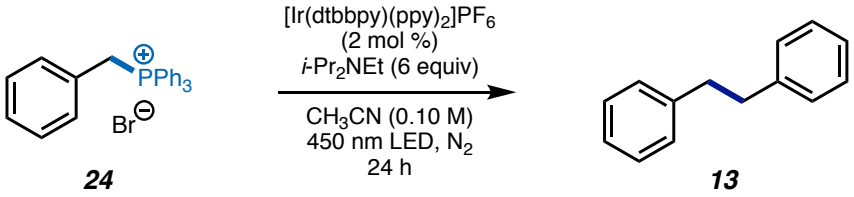
*E-mail: sstevenson@carthage.edu

Table of Contents

Materials and Methods

Commercially available chemicals were purchased from Sigma-Aldrich (St. Louis, MO), Oakwood Chemical (Estill, SC), Combi-blocks (San Diego, CA), and TCI America (Portland, OR). $[Ir(dtbbpy)(ppy)_2]PF_6$ was purchased from Oakwood Chemical, $Ir(ppy)_3$ and $[Ir\{dF(CF_3)ppy\}_2(dtbbpy)]PF_6$ were purchased from Sigma-Aldrich, and $Ru(bpy)_3(PF_6)_2$ was purchased from TCI America. All reagents and photocatalysts were used as received. Solvents were purchased from Sigma-Aldrich and used as received. Photoredox reactions were performed in borosilicate vials or borosilicate round-bottom flasks and irradiated with a Kessil A160WE Controllable LED Aquarium Light, Tuna Blue (450 nm). Qualitative TLC analysis was performed on 250 μm thick, glass backed, F254 silica (Silicycle, Quebec City, Canada). Visualization was accomplished with UV light. Flash chromatography was performed using Silicycle silica gel (SiliaFlash P60, 230-400 mesh). ^1H NMR spectra were acquired on a Bruker Ascend 400 MHz NMR Spectrometer and are reported relative to $SiMe_4$ (δ 0.00).

General procedure for reaction optimization experiments

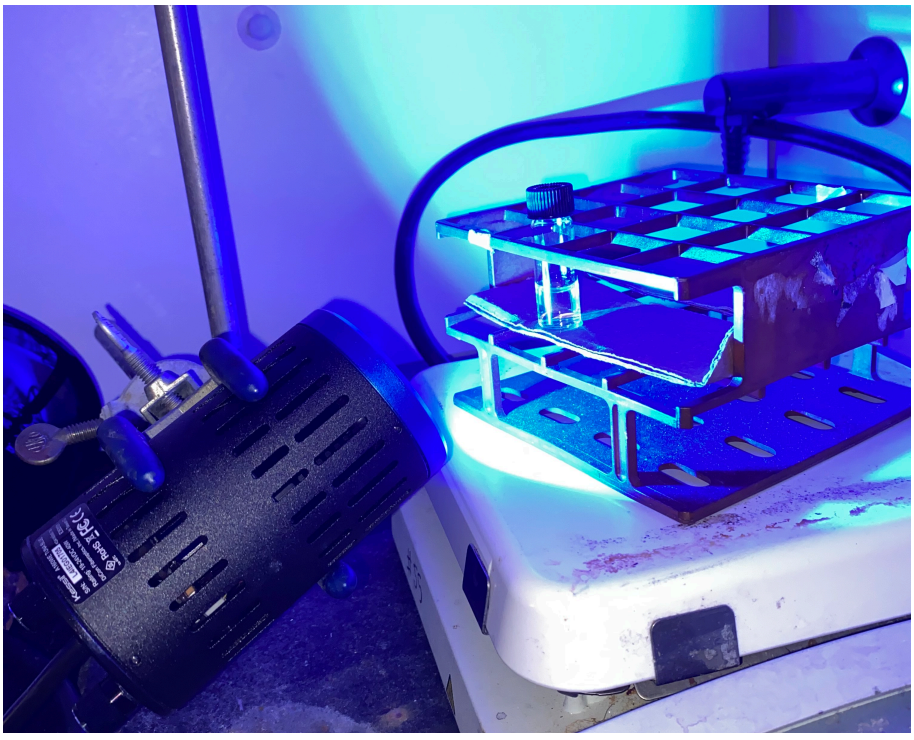


24 ***13***

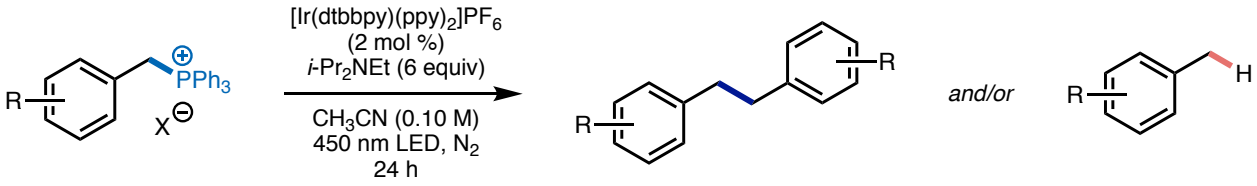
Table 1, entry 5:

To a 1-dram vial containing a stir bar were added benzyltriphenylphosphonium bromide (**24**) (43.3 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), *i*-Pr_2NEt (105 μL, 0.600 mmol, 6 equiv), and CH_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane (17.4 mg, 0.100 mmol, 1 equiv) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^1H NMR spectroscopy to determine the NMR yield of **13**.

Picture of reaction set-up:

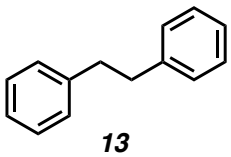


General procedure for photoredox reactions of benzyltriphenylphosphonium salts



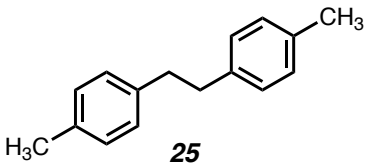
To a 25-mL round bottom flask containing a stir bar were added the benzyltriphenylphosphonium salt (0.250 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (4.6 mg, 5.00 μmol, 2 mol %), *i*-Pr_2NEt (261 μL, 1.50 mmol, 6 equiv), and CH_3CN (2.5 mL, 0.10 M). The vial was sealed with a rubber septum. The flask was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The flask was then clamped over a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~5 cm in a monster pipet), eluting with diethyl ether (~15 mL), then was concentrated by rotary evaporation.

To remove the triphenylphosphine byproduct from the crude reaction mixture, the procedure from Lipshutz was followed.[1] To the crude reaction mixture were added Merrifield's peptide resin (140 mg, 200-400 mesh, extent of labeling: 3.5-4.5 mmol/g Cl^- loading, 1% cross-linked), NaI (84.0 mg, 0.560 mmol, 2.2 equiv), and acetone (1.5 mL, 0.17 M). The round bottom flask was capped and stirred for 24 h at room temperature. After 24 h, the mixture was passed through a short plug of silica (~5 cm in a monster pipet), eluting with diethyl ether (~20 mL), then was concentrated by rotary evaporation. The products were further purified by column chromatography (hexanes → hexanes/ethyl acetate eluent).



13

Prepared according to the general procedure from benzyltriphenylphosphonium bromide (**24**) (0.108 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).
Colorless solid; Yield: 17.7 mg, 78%
All spectroscopic data were consistent with previously reported values.[2]
^1H NMR (400 MHz, $CDCl_3$): δ 7.31-7.27 (m, 4H), 7.22-7.19 (m, 6H), 2.93 (s, 4H).



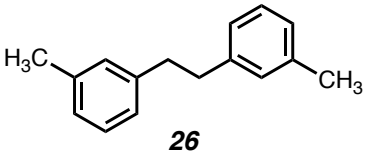
25

Prepared according to the general procedure from (4-methylbenzyl)triphenylphosphonium bromide (**S3**) (0.112 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 23.3 mg, 89%

All spectroscopic data were consistent with previously reported values.[2]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.10 (m, 8H), 2.87 (s, 4H), 2.33 (s, 6H).



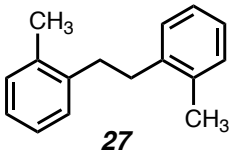
26

Prepared according to the general procedure from (3-methylbenzyl)triphenylphosphonium bromide (**S4**) (0.112 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 16.4 mg, 62%

All spectroscopic data were consistent with previously reported values.[3]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.20 (t, *J* = 7.6 Hz, 2H), 7.05-7.02 (m, 6H), 2.88 (s, 4H), 2.36 (s, 6H).



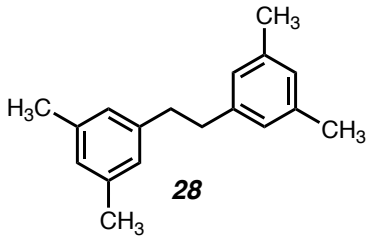
27

Prepared according to the general procedure from (2-methylbenzyl)triphenylphosphonium chloride (**S5**) (0.101 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 13.9 mg, 53%

All spectroscopic data were consistent with previously reported values.[2]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.19-7.11 (m, 8H), 2.86 (s, 4H), 2.33 (s, 6H).



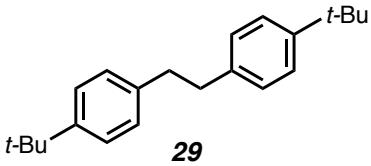
28

Prepared according to the general procedure from (3,5-dimethylbenzyl)triphenylphosphonium bromide (**S6**) (0.115 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 19.5 mg, 65%

All spectroscopic data were consistent with previously reported values.[3]

^{1}H NMR (400 MHz, $CDCl_3$): δ 6.86 (s, 6H), 2.82 (s, 4H), 2.32 (s, 12H).



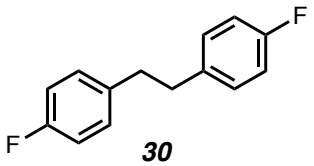
29

Prepared according to the general procedure from (4-*tert*-butylbenzyl)triphenylphosphonium bromide (**S7**) (0.122 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 32.2 mg, 88%

All spectroscopic data were consistent with previously reported values.[2]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34 (d, *J* = 8.0 Hz, 4H), 7.19 (d, *J* = 8.0 Hz, 4H), 2.90 (s, 4H), 1.33 (s, 18H).



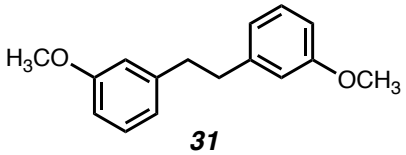
30

Prepared according to the general procedure from (4-fluorobenzyl)triphenylphosphonium chloride (**S8**) (0.102 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 25.6 mg, 94%

All spectroscopic data were consistent with previously reported values.[2]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.09-7.07 (m, 4H), 6.97-6.93 (m, 4H), 2.86 (s, 4H).



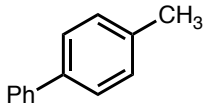
31

Prepared according to the general procedure from (3-methoxybenzyl)triphenylphosphonium chloride (**S9**) (0.105 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 9:1 hexanes/EtOAc).

Colorless solid; Yield: 26.2 mg, 86%

All spectroscopic data were consistent with previously reported values.[4]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.20 (t, *J* = 7.6 Hz, 2H), 6.80-6.73 (m, 6H), 3.78 (s, 6H), 2.89 (s, 4H).



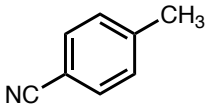
32

Prepared according to the general procedure from (4-phenylbenzyl)triphenylphosphonium bromide (**S10**) (0.127 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 20:1 hexanes/EtOAc).

Colorless solid; Yield: 38.2 mg, 91%

All spectroscopic data were consistent with previously reported values.[5]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.58 (d, *J* = 7.6 Hz, 2H), 7.50 (d, *J* = 8.0 Hz, 2H), 7.44 (t, *J* = 7.6 Hz, 2H), 7.33 (t, *J* = 7.6 Hz, 1H), 7.26 (d, *J* = 8.0 Hz, 2H), 2.41 (s, 3H).



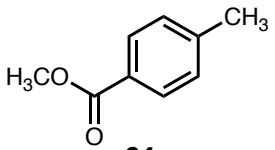
33

Prepared according to the general procedure from (4-cyanobenzyl)triphenylphosphonium bromide (**S11**) (0.115 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 9:1 hexanes/EtOAc).

Colorless oil; Yield: 26.9 mg, 92%

All spectroscopic data were consistent with previously reported values.[6]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 8.0 Hz, 2H), 7.27 (d, *J* = 8.0 Hz, 2H), 2.42 (s, 3H).



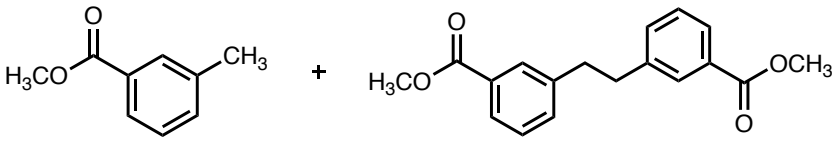
34

Prepared according to the general procedure from [4-(methoxycarbonyl)benzyl]triphenylphosphonium bromide (**45**) (0.123 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 9:1 hexanes/EtOAc).

Colorless oil; Yield: 32.2 mg, 86%

All spectroscopic data were consistent with previously reported values.[7]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92 (d, *J* = 8.0 Hz, 2H), 7.23 (d, *J* = 8.0 Hz, 2H), 3.90 (s, 3H), 2.41 (s, 3H).

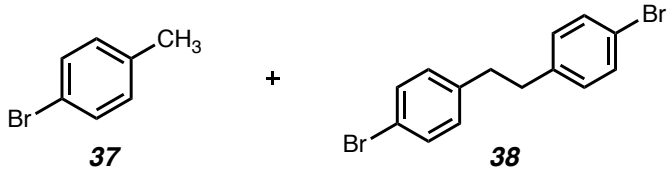


35 ***36***

Prepared according to the general procedure for reaction optimization experiments from [3-(methoxycarbonyl)benzyl]triphenylphosphonium bromide (**S12**) (49.1 mg, 0.10 mmol). Yields were determined by ^{1}H NMR with dibromomethane as an internal standard.

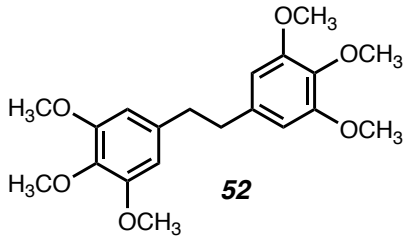
35: 89% NMR yield. Identity confirmed by comparison with literature ^{1}H NMR spectrum.[8] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86-7.83 (m, 2H), 7.38-7.30 (m, 2H), 3.91 (s, 3H), 2.40 (s, 3H).

36: 5% NMR yield. Identity confirmed by comparison with literature ^{1}H NMR spectrum.[9]



37 ***38***

Prepared according to the general procedure for reaction optimization experiments from (4-bromobenzyl)triphenylphosphonium bromide (**S13**) (51.2 mg, 0.10 mmol). A complex mixture of products was obtained which contained 28% NMR yield of **37** and 23% NMR yield **38**, as confirmed by comparison with literature ^{1}H NMR spectra (**37**[10], **38**[2]). Yields were determined by ^{1}H NMR with dibromomethane as an internal standard.



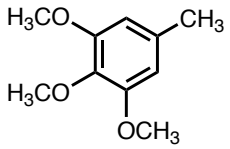
52

Prepared according to the general procedure from (3,4,5-trimethoxybenzyl)triphenylphosphonium chloride (**51**) (0.120 g, 0.25 mmol). The product was further purified by column chromatography (hexanes → 2:1 hexanes/EtOAc) to separate brittonin A from the minor product, 3,4,5-trimethoxytoluene (**S14**). All spectroscopic data were consistent with previously reported values.

brittonin A (**52**)[4]: Colorless solid; Yield: 20.0 mg, 44%

R_f = 0.34 in 2:1 hexanes/EtOAc, visualized by UV

^{1}H NMR (400 MHz, $CDCl_3$): δ 6.36 (s, 4H), 3.82 (s, 18H), 2.84 (s, 4H).



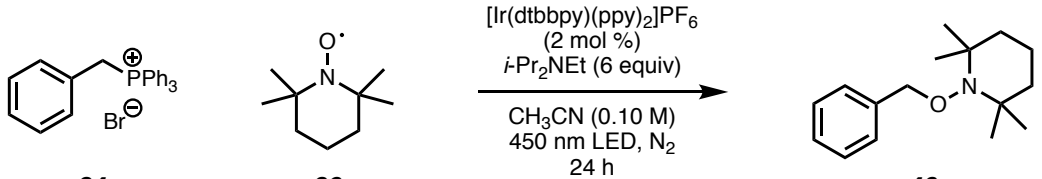
S14

3,4,5-trimethoxytoluene (**S14**)[7]: 3,4,5-trimethoxytoluene: Colorless oil; Yield: 8.8 mg, 19%

R_f = 0.71 in 2:1 hexanes/EtOAc, visualized by UV

^{1}H NMR (400 MHz, $CDCl_3$): δ 6.39 (s, 2H), 3.84 (s, 6H), 3.82, (s, 3H), 2.31 (s, 3H).

TEMPO coupling experiment

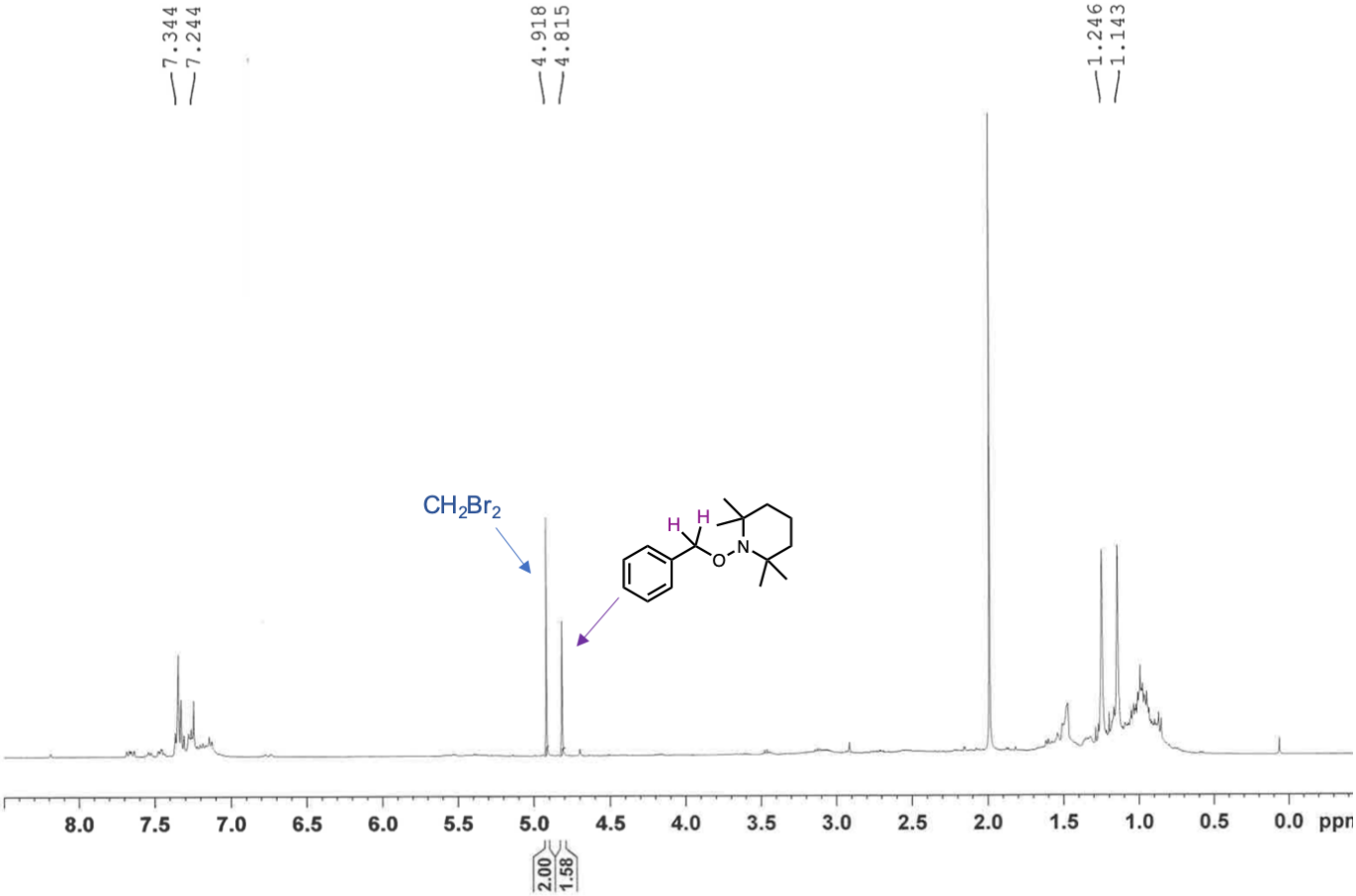


24 (1 equiv) ***39*** (0.5 equiv) ***40*** 79% yield

To a 1-dram vial containing a stir bar were added benzyltriphenylphosphonium bromide (**24**) (43.3 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), *i*-Pr_2NEt (105 μL, 0.600 mmol, 6 equiv), TEMPO (**39**) (7.8 mg, 0.0500 mmol, 0.5 equiv), and CH_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane relative to TEMPO (8.7 mg, 0.0500 mmol) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^1H NMR spectroscopy.

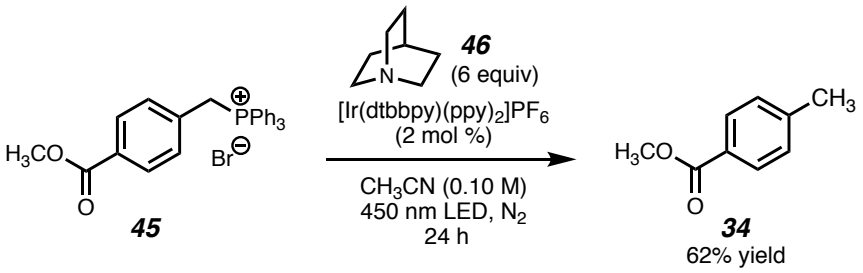
Result: 79% NMR yield **40**. The product was identified by comparison with the literature ^1H NMR spectrum.[11] (*see crude NMR on next page*)

^{1}H NMR spectrum of crude reaction mixture with CH_2Br_2 internal standard:



HAT and deuterium incorporation experiments

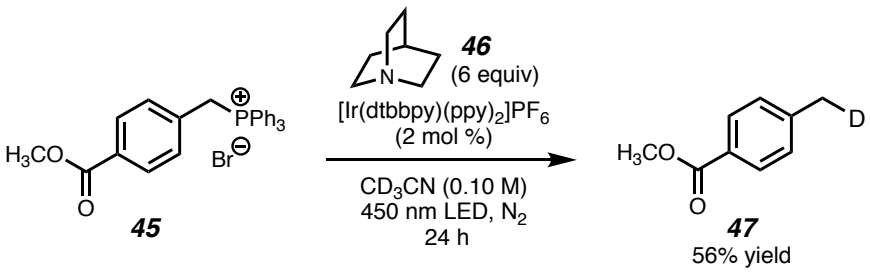
Scheme 6a[i]



To a 1-dram vial containing a stir bar were added benzyltriphenylphosphonium salt **45** (49.1 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), quinuclidine (66.7 mg, 0.600 mmol, 6 equiv), and CH_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane (17.4 mg, 0.100 mmol, 1 equiv) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^1H NMR spectroscopy.

Result: 62% NMR yield **34**

Scheme 6a[ii]

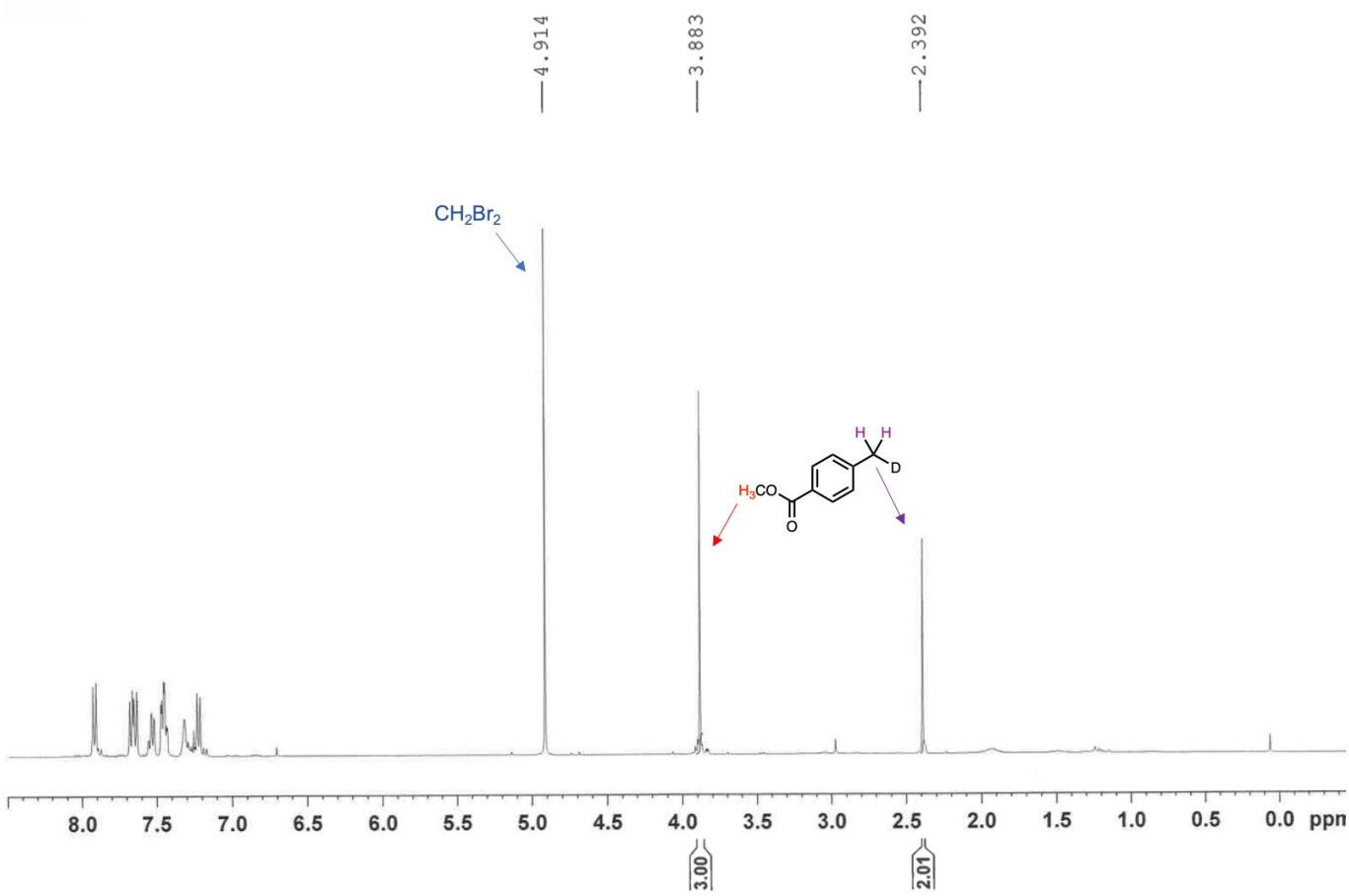


To a 1-dram vial containing a stir bar were added benzyltriphenylphosphonium salt **45** (49.1 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), quinuclidine (66.7 mg, 0.600 mmol, 6 equiv), and CD_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h

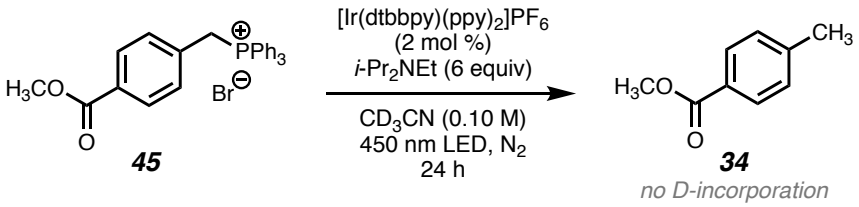
with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane (17.4 mg, 0.100 mmol, 1 equiv) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^{1}H NMR spectroscopy.

Result: 56% NMR yield **47**. The product was identified by comparison with the literature ^{1}H NMR spectrum.[12]

^{1}H NMR spectrum of crude reaction mixture with CH_2Br_2 internal standard:



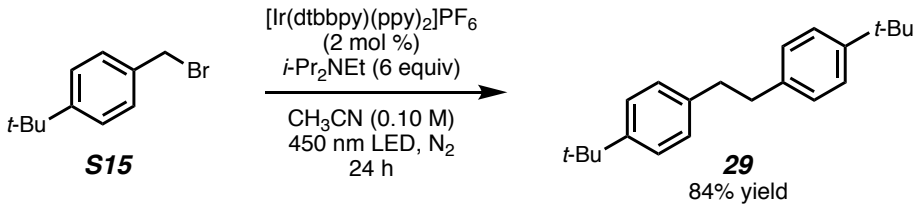
Scheme 6b



To a 1-dram vial containing a stir bar were added benzyltriphenylphosphonium salt **45** (49.1 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), *i*-Pr_2NEt (105 μL, 0.600 mmol, 6 equiv), and CD_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane (17.4 mg, 0.100 mmol, 1 equiv) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^1H NMR spectroscopy.

Result: 90% NMR yield **34**

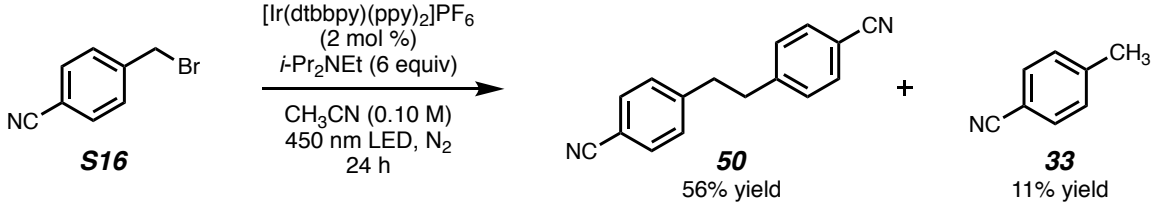
Reactions of benzyl bromides



S15 ***29*** 84% yield

To a 1-dram vial containing a stir bar were added 4-*tert*-butylbenzyl bromide (**S15**) (22.7 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), *i*-Pr_2NEt (105 μL, 0.600 mmol, 6 equiv), and CH_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane (17.4 mg, 0.100 mmol, 1 equiv) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^1H NMR spectroscopy.

Result: 84% NMR yield **29**

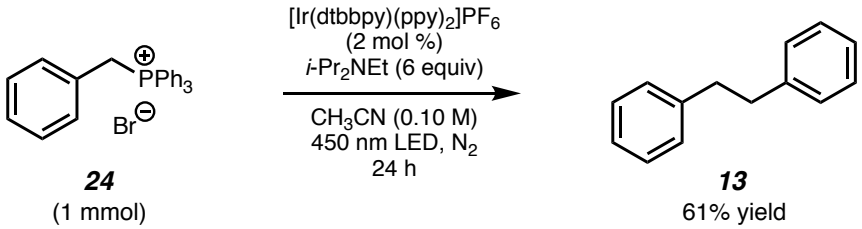


S16 ***50*** 56% yield ***33*** 11% yield

To a 1-dram vial containing a stir bar were added 4-cyanobenzyl bromide (**S16**) (19.6 mg, 0.100 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (1.8 mg, 2.00 μmol, 2 mol %), *i*-Pr_2NEt (105 μL, 0.600 mmol, 6 equiv), and CH_3CN (1.0 mL, 0.10 M). The vial was capped with an open-top screw cap fitted with a Teflon septum. The vial was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The vial was then placed on a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~3 cm in a monster pipet), eluting with diethyl ether (~10 mL), then was concentrated by rotary evaporation. A solution containing 1 equiv of dibromomethane (17.4 mg, 0.100 mmol, 1 equiv) in $CDCl_3$ was added and the crude reaction mixture was analyzed by ^1H NMR spectroscopy.

Result: 56% NMR yield **50**,[13] 11% NMR yield **33**

1 mmol scale reaction



24
(1 mmol)

13
61% yield

To a 50-mL round bottom flask containing a stir bar were added benzyltriphenylphosphonium bromide (**24**) (0.433 g, 1.00 mmol, 1 equiv), $[Ir(dtbbpy)(ppy)_2]PF_6$ (18.3 mg, 0.0200 mmol, 2 mol %), *i*-Pr_2NEt (1.04 mL, 6.00 mmol, 6 equiv), and CH_3CN (10 mL, 0.10 M). The vial was sealed with a rubber septum. The flask was degassed by bubbling N_2 gas through the reaction mixture for 3 min. The flask was then clamped over a stir plate, approximately 5 cm from the light source, and irradiated with a blue LED for 24 h with stirring. After 24 h, the reaction mixture was passed through a short plug of silica (~5 cm in a monster pipet), eluting with diethyl ether (~20 mL), then was concentrated by rotary evaporation.

To remove the triphenylphosphine byproduct from the crude reaction mixture, the procedure from Lipshutz was followed.[1] To the crude reaction mixture were added Merrifield's peptide resin (0.560 g, 200-400 mesh, extent of labeling: 3.5-4.5 mmol/g Cl^- loading, 1% cross-linked), NaI (0.336 g), and acetone (6 mL). The round bottom flask was capped and stirred for 24 h at room temperature. After 24 h, the mixture was passed through a short plug of silica (~5 cm in a monster pipet), eluting with diethyl ether (~30 mL), then was concentrated by rotary evaporation. The product was further purified by column chromatography (hexanes eluent) to yield bibenzyl (**13**) (56.0 mg, 61% yield) as a white solid.

Representative procedure for synthesis of starting materials

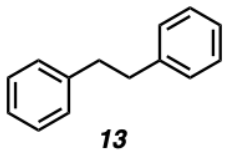
To a 250-mL round bottom flask with a stir bar were added the benzyl bromide (or benzyl chloride) (6.30 mmol, 1.1 equiv), triphenylphosphine (5.70 mmol, 1 equiv), and toluene (20 mL, 0.29 M). The flask was fitted with a condenser and the reaction mixture was refluxed under N_2 with stirring overnight. During this time, the product precipitated out of solution. After cooling to room temperature, the reaction mixture was vacuum filtered through a fritted glass funnel to collect the triphenylphosphonium salt. The product was rinsed with toluene (20 mL) and petroleum ether (20 mL). The product was dried under vacuum for 1 h.

All spectroscopic data were consistent with previously reported values:

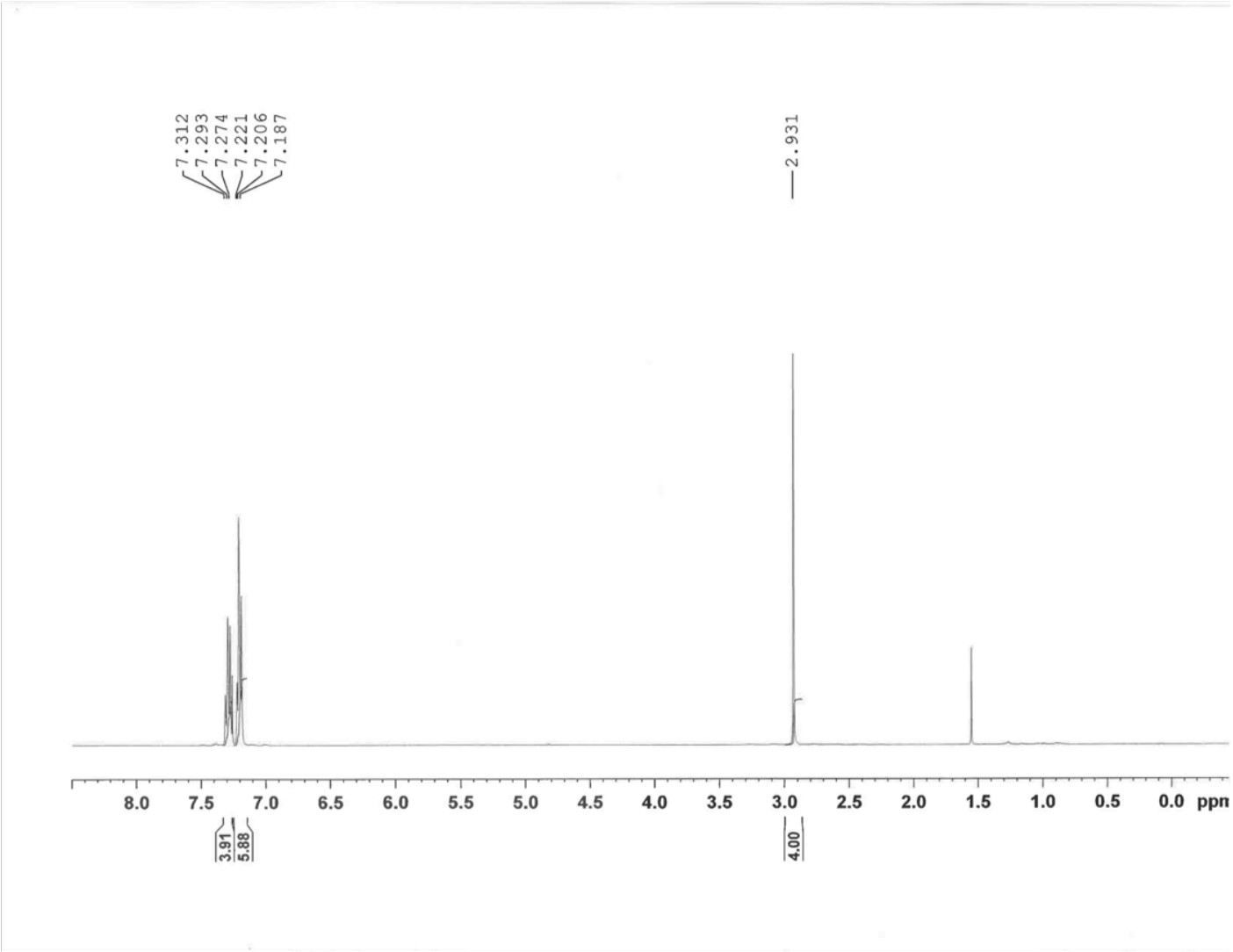
- benzyltriphenylphosphonium bromide (**24**)[14]
- benzyltriphenylphosphonium chloride (**S1**) (purchased from Sigma-Aldrich)
- benzyltriphenylphosphonium tetrafluoroborate (**S2**)[15]
- (4-methylbenzyl)triphenylphosphonium bromide (**S3**)[16]
- (3-methylbenzyl)triphenylphosphonium bromide (**S4**)[17]
- (2-methylbenzyl)triphenylphosphonium chloride (**S5**)[17]
- (3,5-dimethylbenzyl)triphenylphosphonium bromide (**S6**)[17]
- (4-*tert*-butylbenzyl)triphenylphosphonium bromide (**S7**)[17]
- (4-fluorobenzyl)triphenylphosphonium chloride (**S8**) (purchased from Combi-blocks)
- (3-methoxybenzyl)triphenylphosphonium chloride (**S9**) (purchased from Combi-blocks)
- (4-phenylbenzyl)triphenylphosphonium bromide (**S10**):
    - ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.80-7.19 (m, 24H), 5.49 (d, *J* = 14.4 Hz, 1H).
- (4-cyanobenzyl)triphenylphosphonium bromide (**S11**)[17]
- [4-(methoxycarbonyl)benzyl]triphenylphosphonium bromide (**45**)[18]
- [3-(methoxycarbonyl)benzyl]triphenylphosphonium bromide (**S12**):
    - ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.90-7.88 (m, 1H), 7.78-7.76 (m, 10H), 7.69-7.64 (m, 6H), 7.38 (s, 1H), 7.30-7.28 (m, 1H), 5.58 (d, *J* = 14.4 Hz, 1H), 3.80 (s, 3H).
- (4-bromobenzyl)triphenylphosphonium bromide (**S13**)[17]
- (3,4,5-trimethoxybenzyl)triphenylphosphonium chloride (**51**)[19]

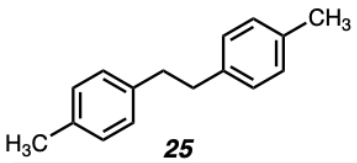
Synthesis of benzyltriphenylphosphonium tetrafluoroborate (**S2**): A solution of benzyltriphenylphosphonium bromide (**24**) (0.289 g, 0.666 mmol) in 10 mL dichloromethane was prepared. Another solution of sodium tetrafluoroborate (2.5 g, 22.8 mmol) in 50 mL water was prepared. To a separatory funnel were added the solution of **24** and 7 mL of the sodium tetrafluoroborate solution. The separatory funnel was shaken vigorously with venting for ~1 minute to mix the layers. The layers were separated. The organic layer was returned to the separatory funnel and washed two more times with 7 mL of the sodium tetrafluoroborate solution, each time shaking the layers vigorously for ~1 minute. Then the organic layer was washed with water (3 x 7 mL). The solvent was removed by rotary evaporation and the solid product (**S2**) was dried under vacuum for 1 h.

^{1}H NMR spectra

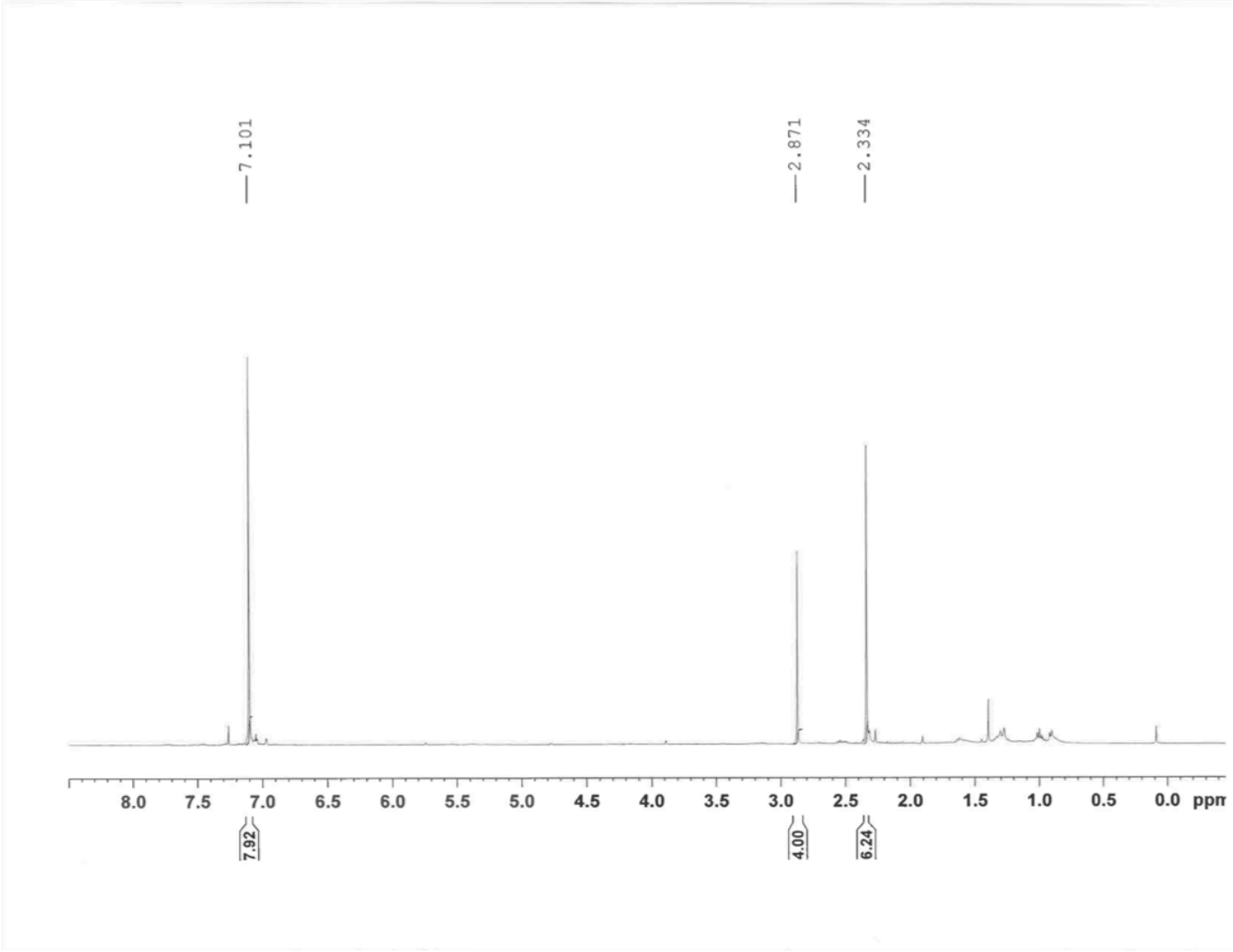


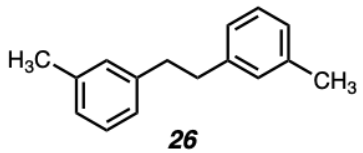
13



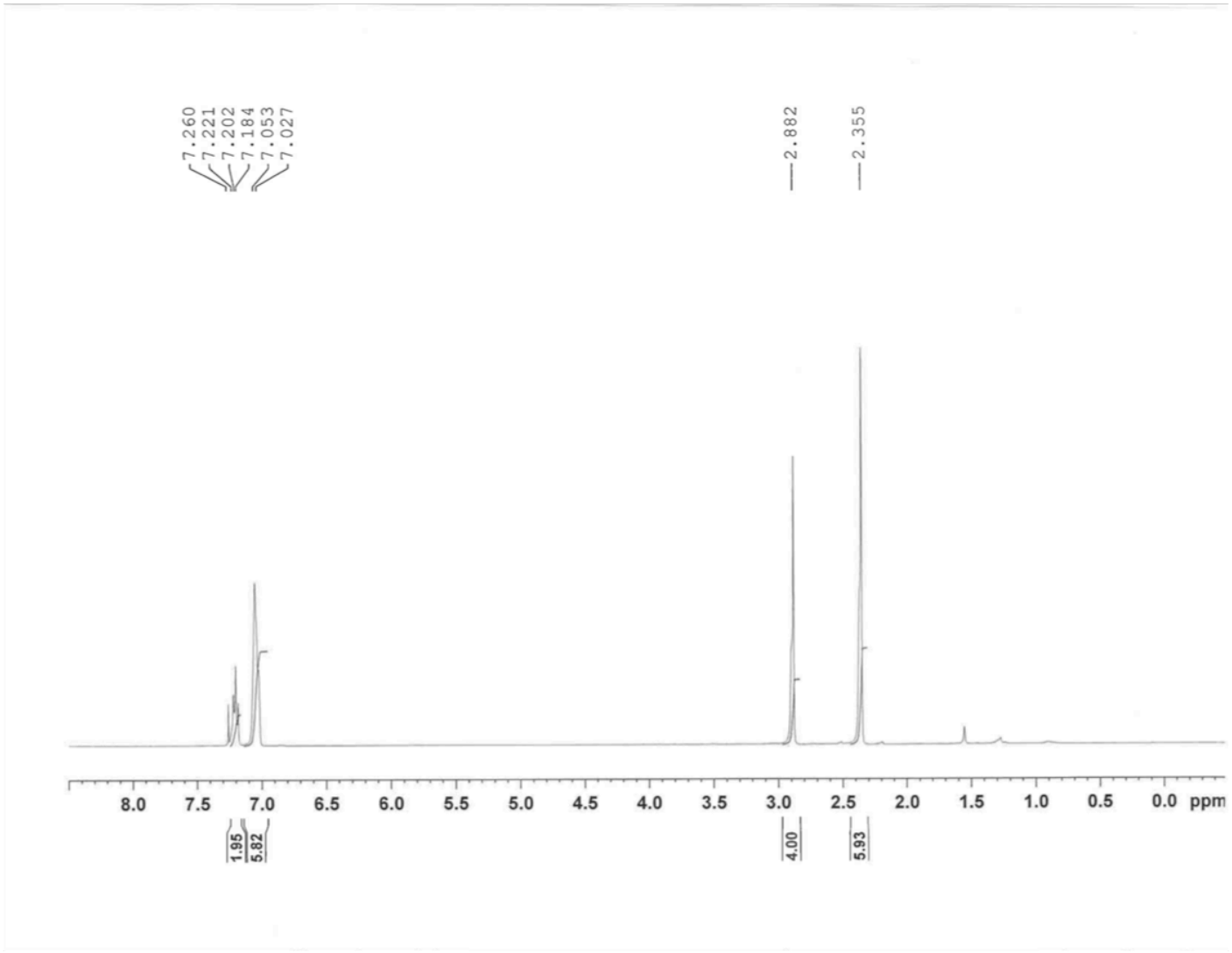

CH3
H3C

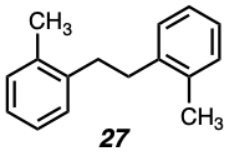
25


7.101
2.871
2.334
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
7.92
4.00
6.24

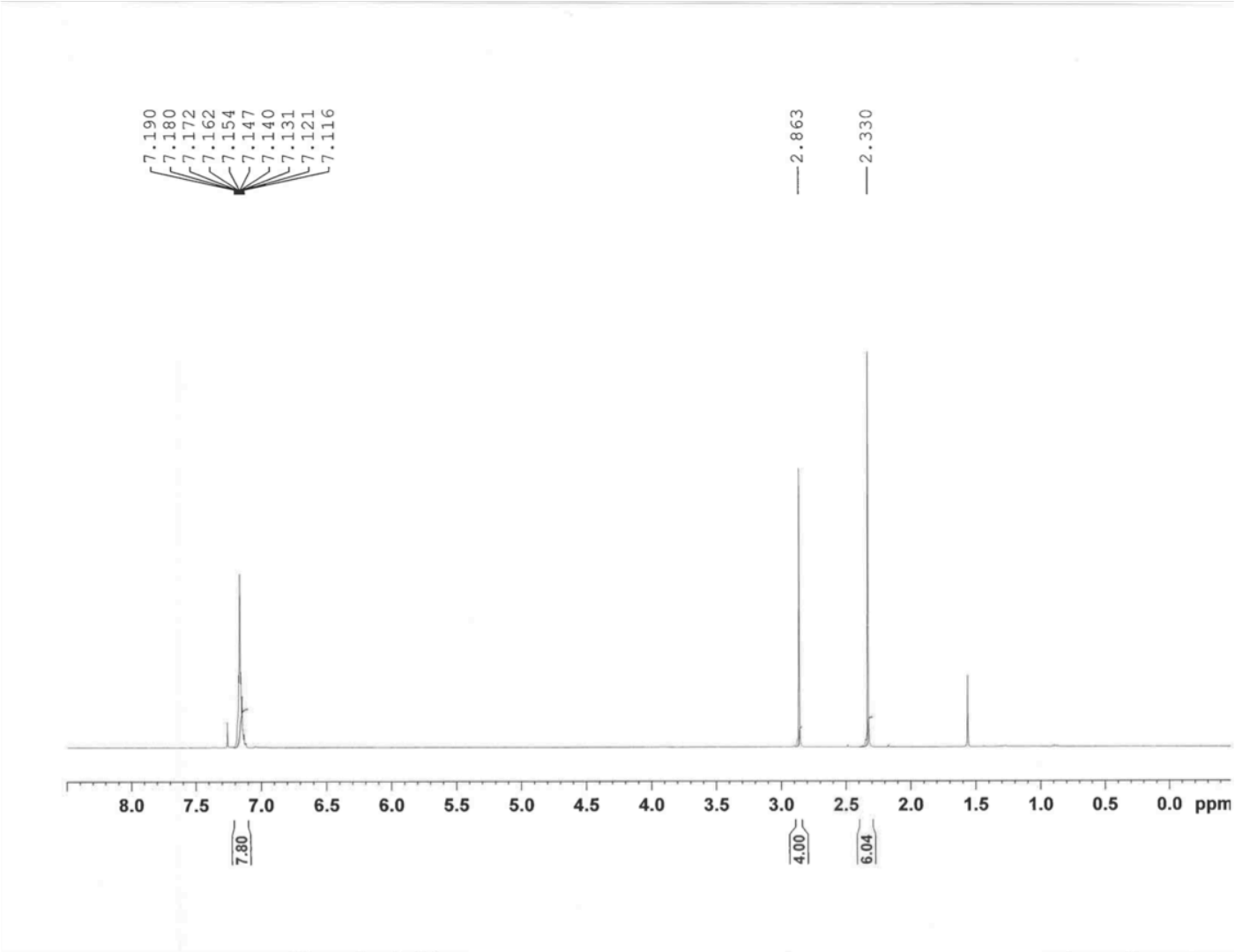

H3C
CH3

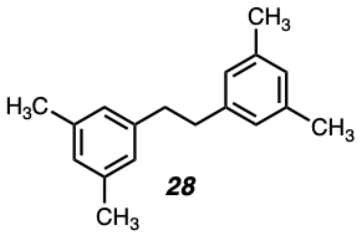
26


7.260
7.221
7.202
7.184
7.053
7.027
2.882
2.355
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.95
5.82
4.00
5.93

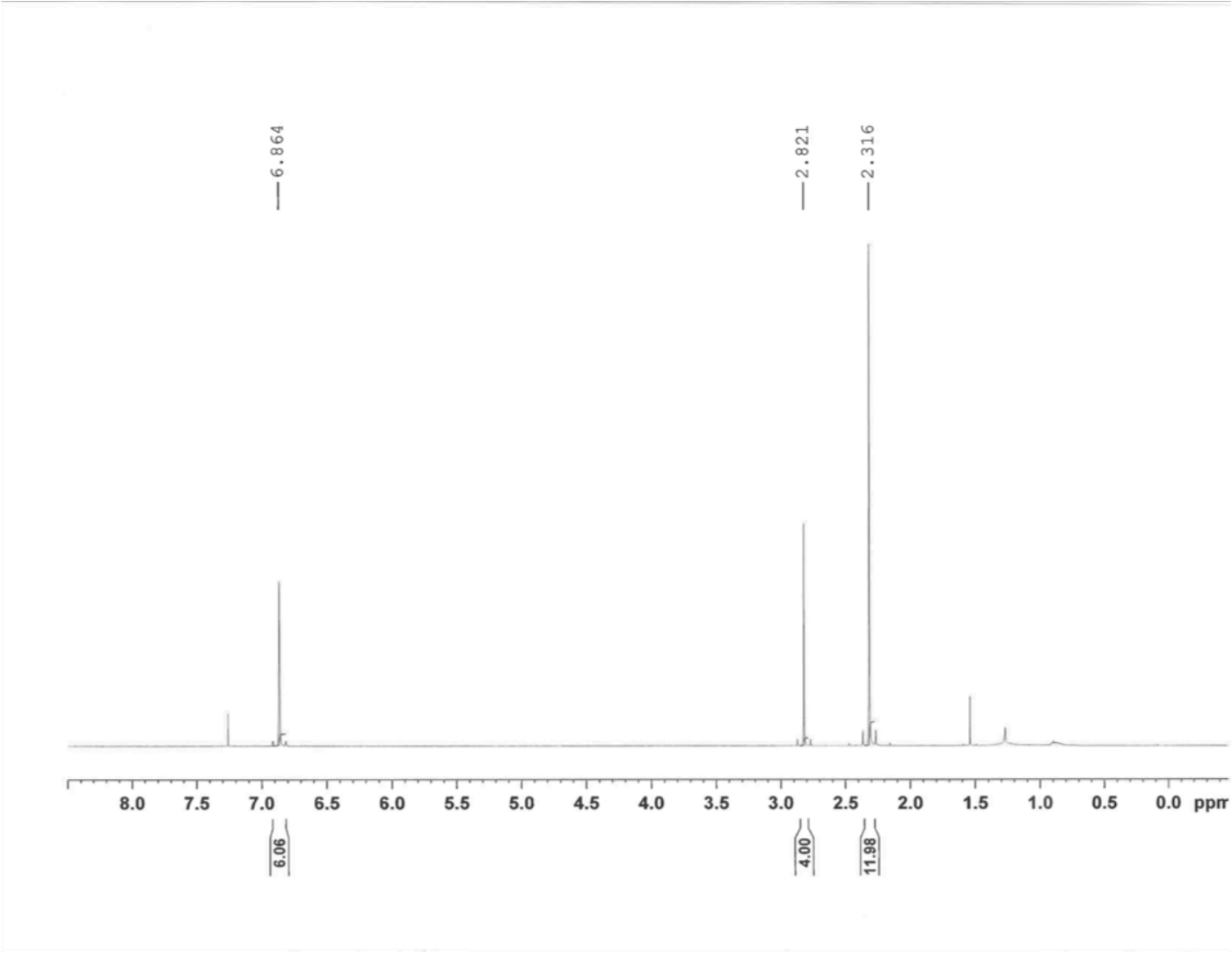

CH3
CH3

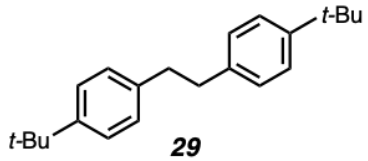
27


7.190
7.180
7.172
7.162
7.154
7.147
7.140
7.131
7.121
7.116
2.863
2.330
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
7.80
4.00
6.04

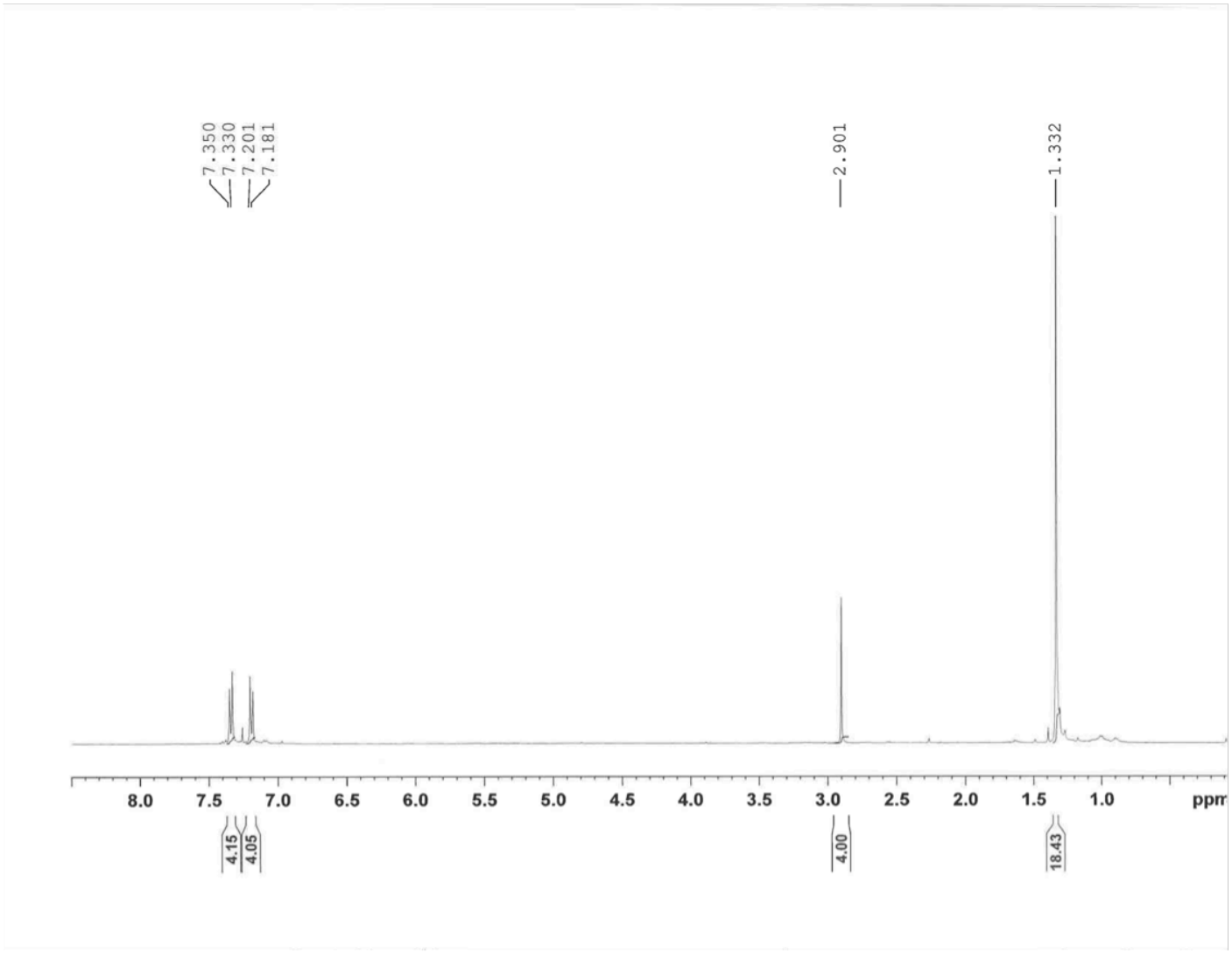

CH3
H3C
CH3
CH3

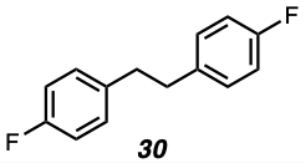
28


6.864
2.821
2.316
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
6.06
4.00
11.98

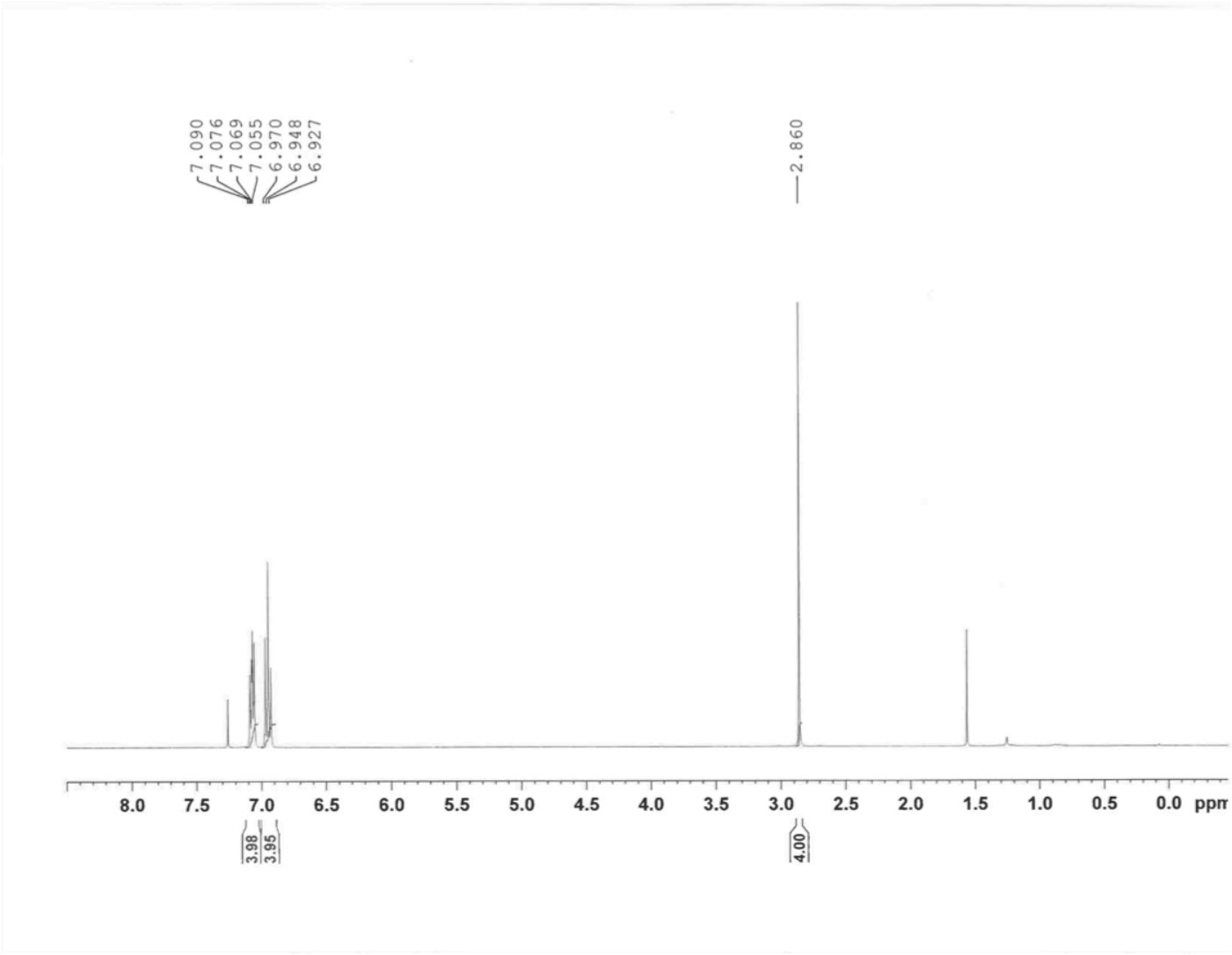

t-Bu
t-Bu

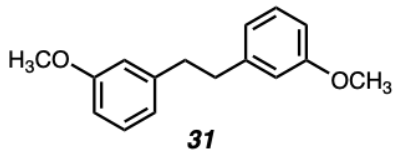
29


7.350
7.330
7.201
7.181
2.901
1.332
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
ppm
4.15
4.05
4.00
18.43

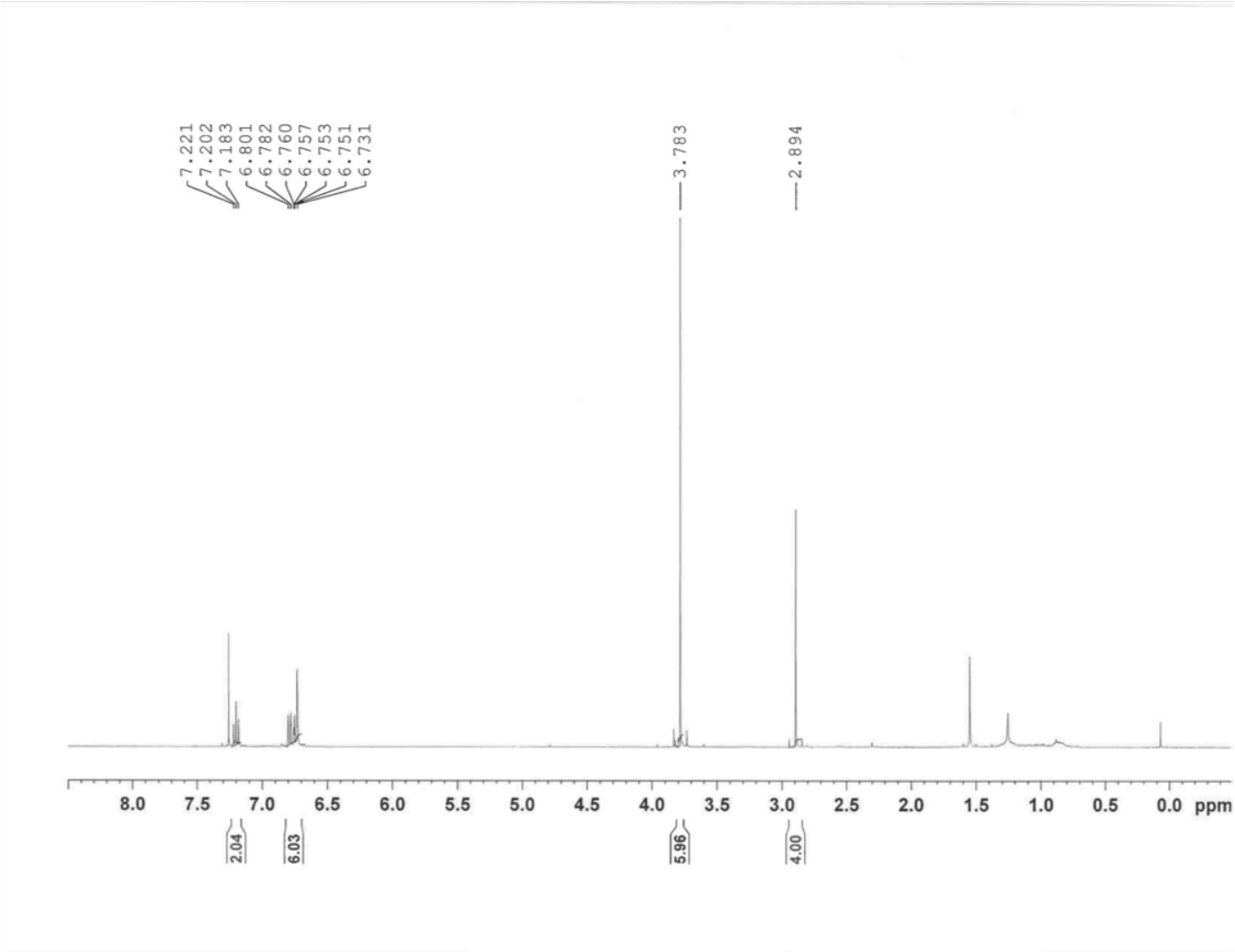

F
F

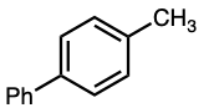
30


7.090
7.076
7.069
7.055
6.970
6.948
6.927
2.860
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
3.98
3.95
4.00

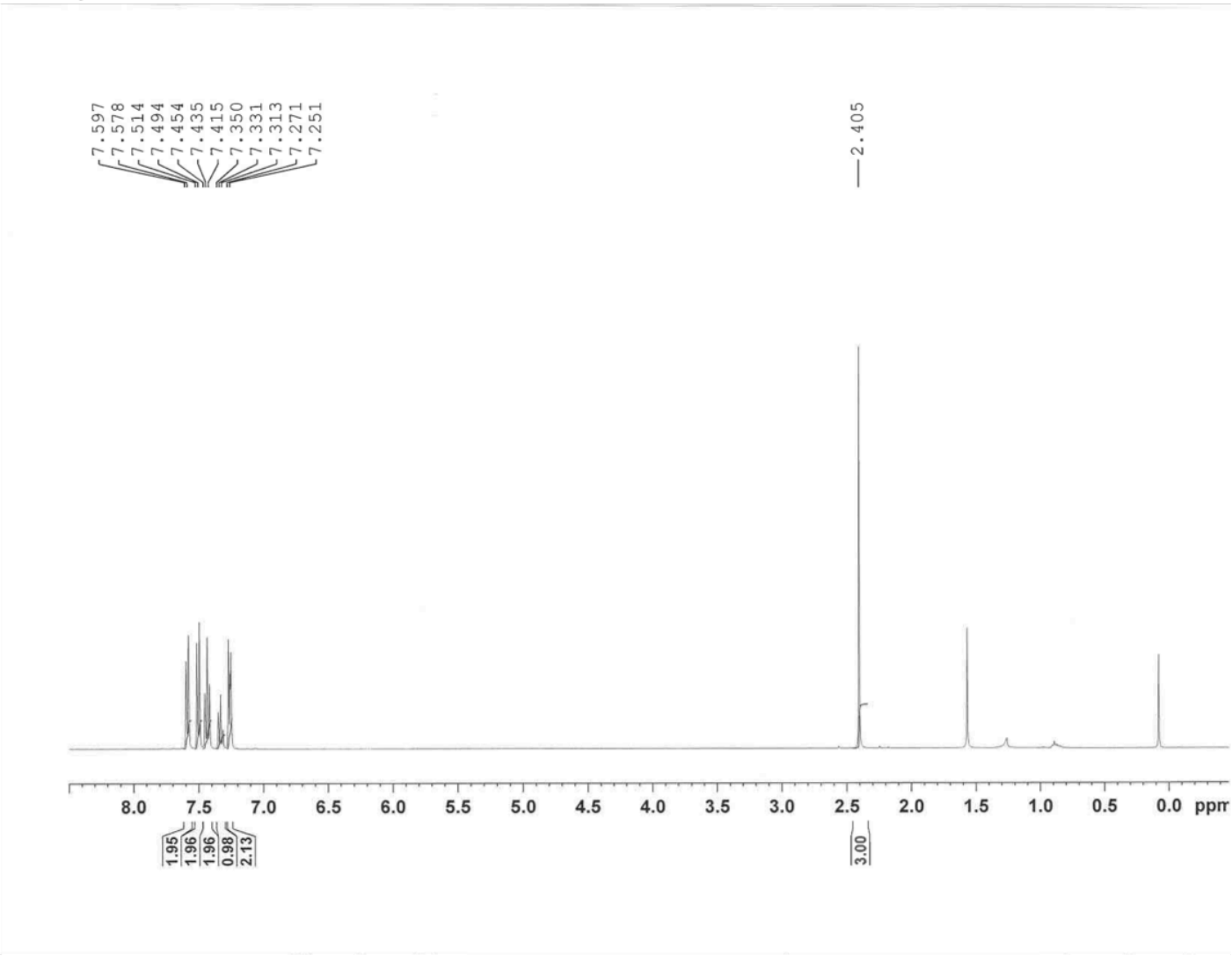

H3CO
OCH3

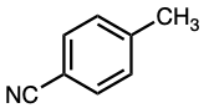
31


7.221
7.202
7.183
6.801
6.782
6.760
6.757
6.753
6.751
6.731
3.783
2.894
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0 ppm
2.04
6.03
5.96
4.00

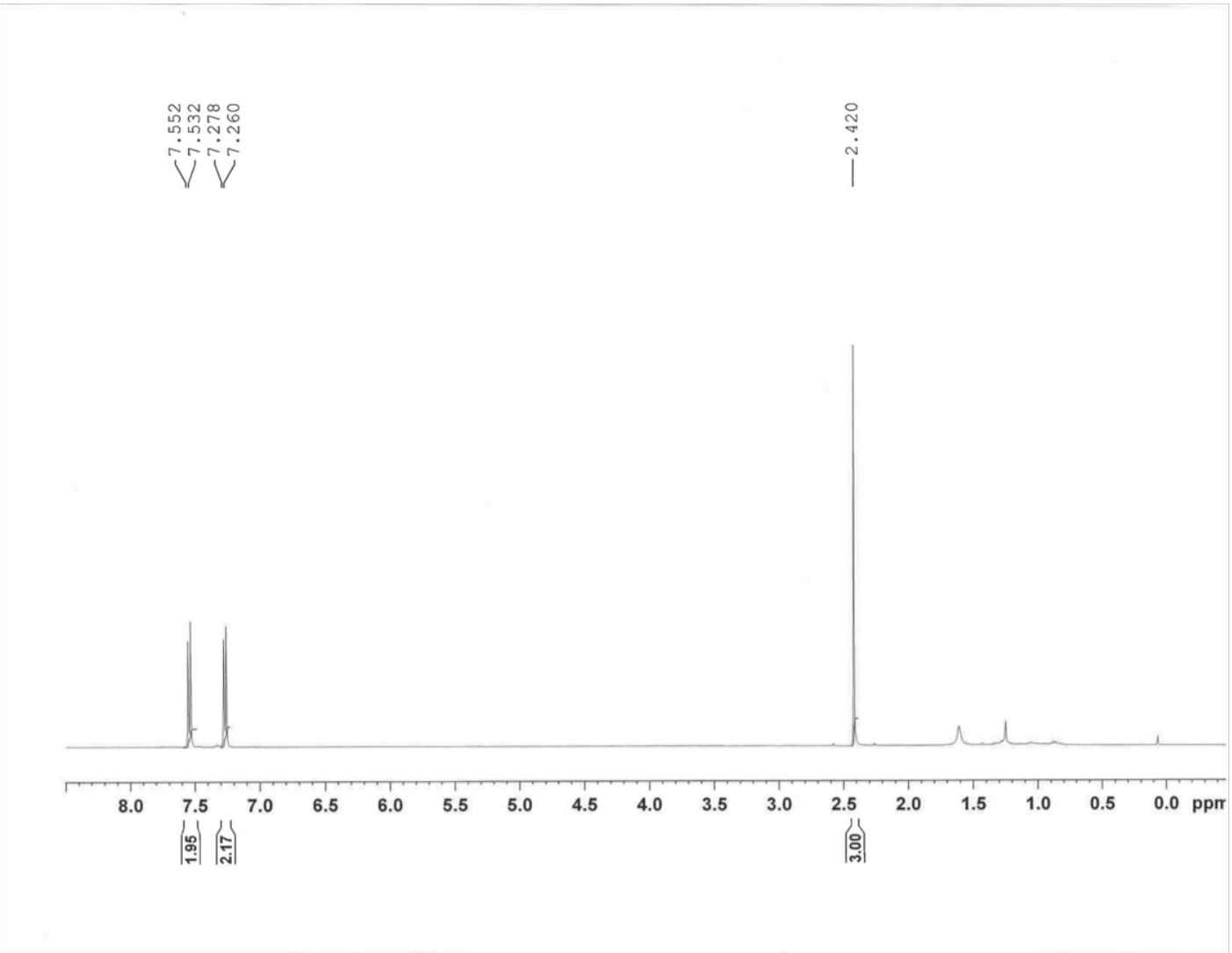

CH3
Ph

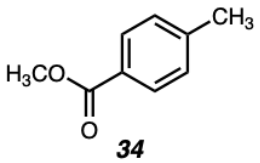
32


7.597
7.578
7.514
7.494
7.454
7.435
7.415
7.350
7.331
7.313
7.271
7.251
2.405
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.95
1.96
1.96
0.98
2.13
3.00

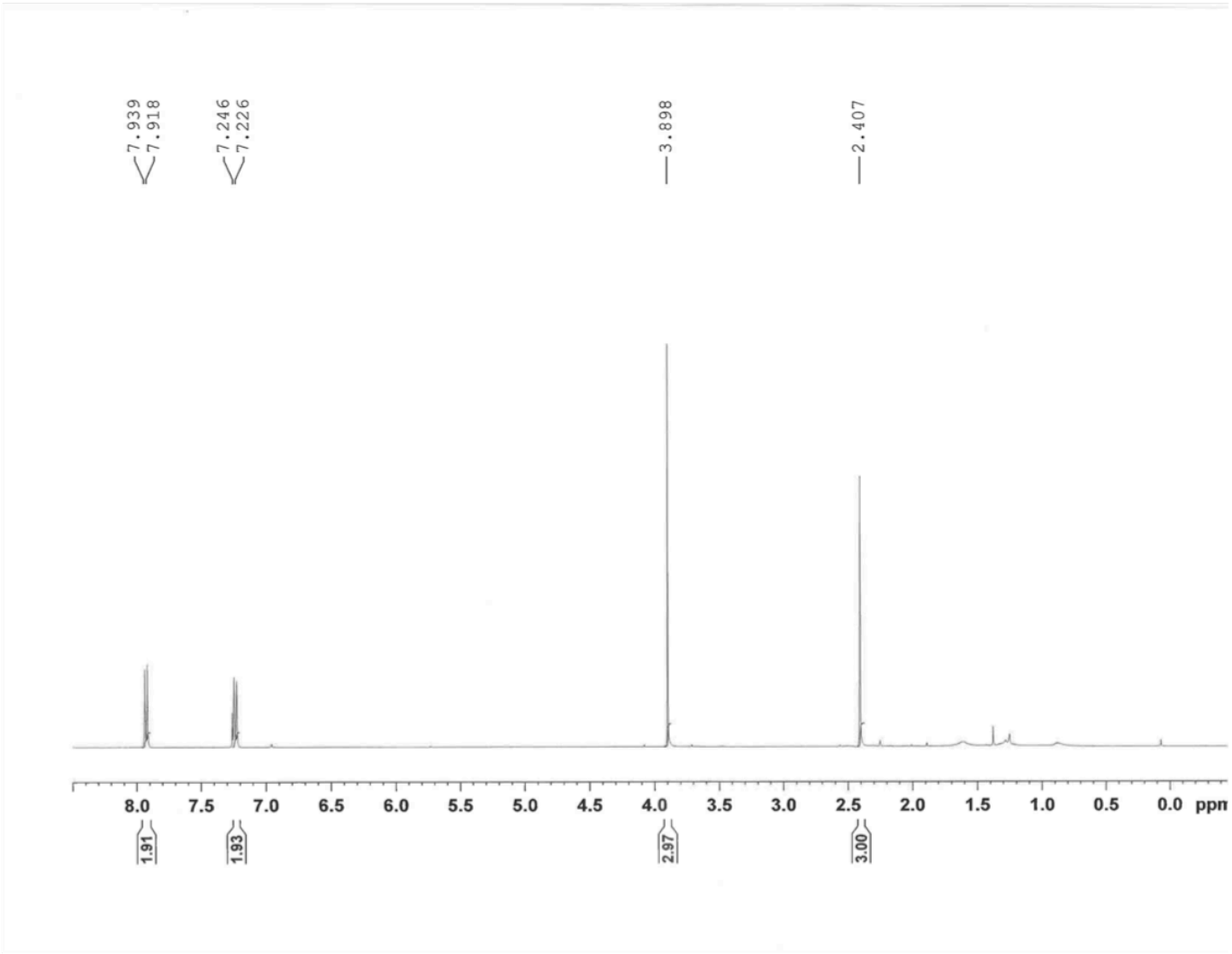

CH3
NC

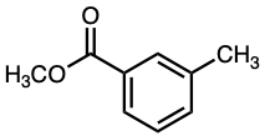
33


7.552
7.532
7.278
7.260
2.420
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.95
2.17
3.00

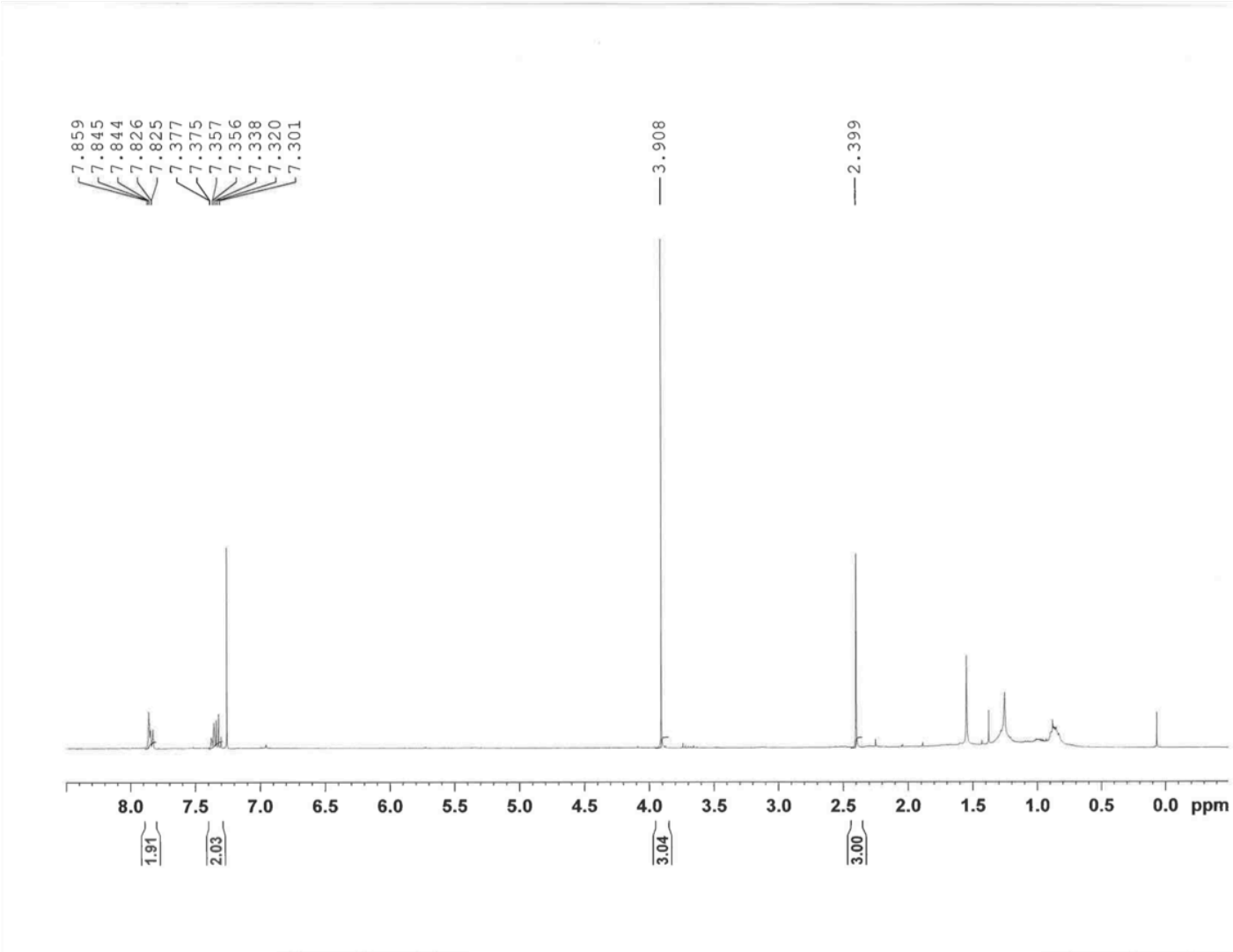

CH3
H3CO
O

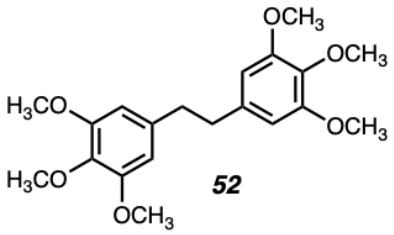
34


7.939
7.918
7.246
7.226
3.898
2.407
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0 ppm
1.91
1.93
2.97
3.00

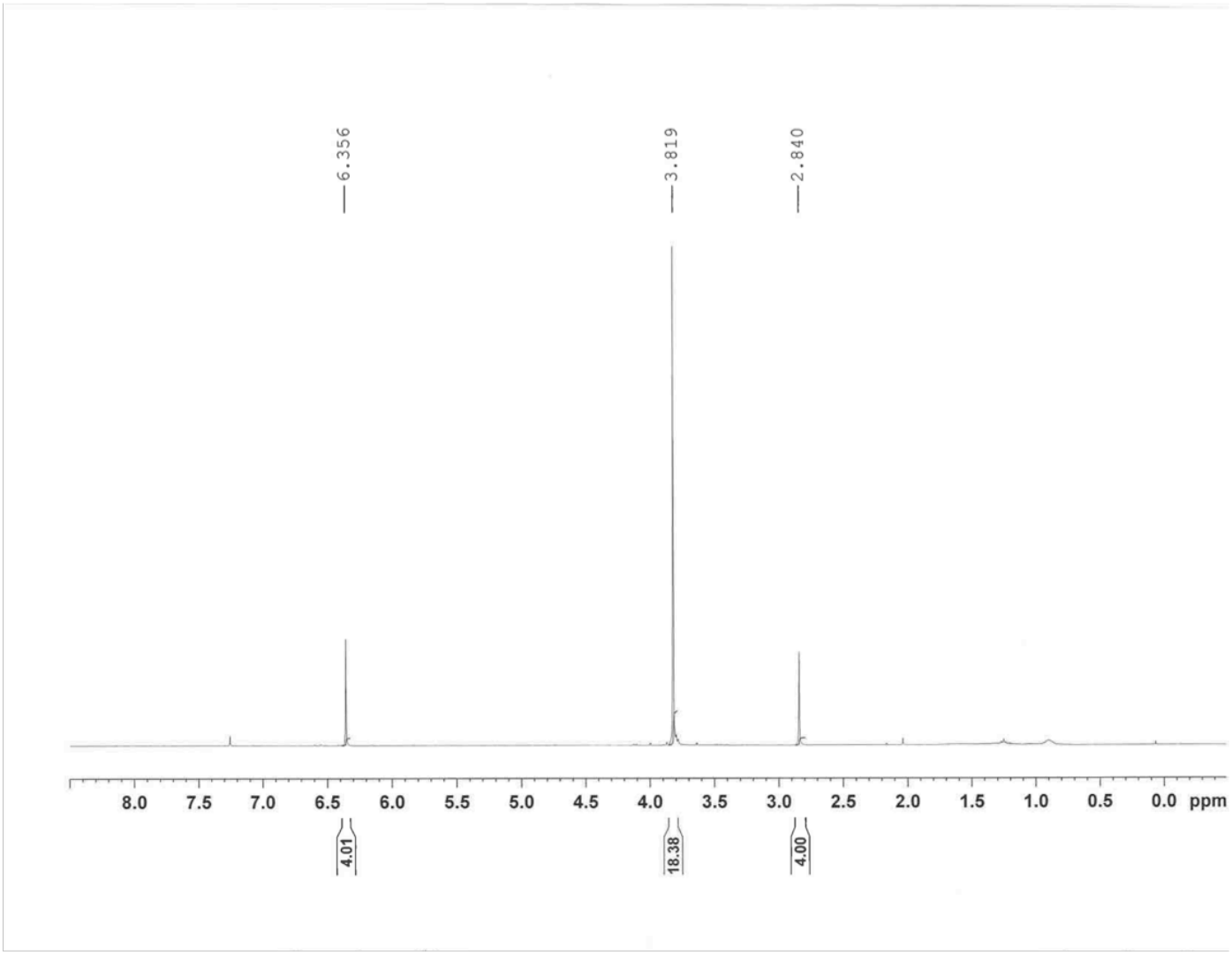

O
H3CO
CH3

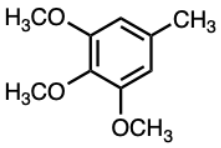
35


7.859
7.845
7.844
7.826
7.825
7.377
7.375
7.357
7.356
7.338
7.320
7.301
3.908
2.399
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.91
2.03
3.04
3.00

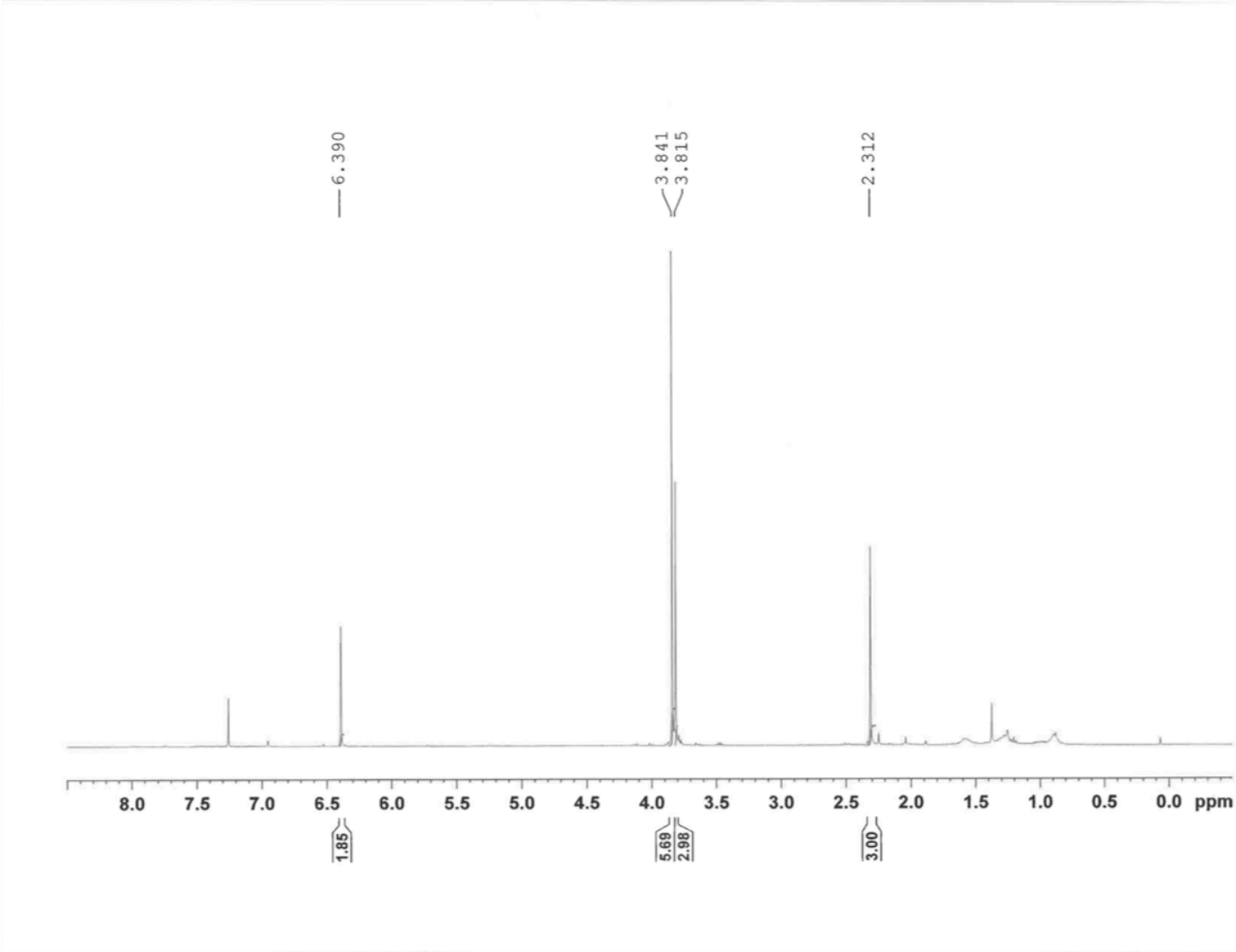

OCH3
OCH3
H3CO
OCH3
H3CO
OCH3

52


6.356
3.819
2.840
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
4.01
18.38
4.00


H3CO
CH3
H3CO
OCH3

S14


6.390
3.841
3.815
2.312
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.85
5.69
2.98
3.00

References

[1] B. H. Lipshutz and P. A. Blomgren, *Org. Lett.* 2001, **3**, 1869–1871.

[2] K. Sato, Y. Inoue, T. Mori, A. Sakaue, A. Tarui, M. Omote, I. Kumadaki and A. Ando., *Org. Lett.,* 2014, **16**, 3756–3759.

[3] M. Blangetti, P. Fleming and D. F. O'Shea, *Beilstein J. Org. Chem*., 2011, **7**, 1249–1254.

[4] G. Park, S. Y. Yi, J. Jung, E. J. Cho and Y. You, *Eur. J. Org. Chem*., 2016, **22**, 17790–17799.

[5] S. Ichii, G. Hamasaka and Y. Uozumi, *Chem. Asian J.,* 2019, **14**, 3850–3854.

[6] P. Y. Yeung, C. M. So, C. P. Lau and F. Y. Kwong, *Org. Lett.,* 2011, **13**, 648–651.

[7] H. R. Diéguez, A. López, V. Domingo, J. F. Arteaga, J. A. Dobado, M. M. Herrador, J. F. Quílez del Moral and A. F. Barrero, *J. Am. Chem. Soc.,* 2010, **132**, 254–259.

[8] C. Liu, J. Wang, L. Meng, Y. Deng, Y. Li and A. Lei, *Angew. Chem. Int. Ed*., 2011, **50**, 5144–5148.

[9] C. D. Mboyi, S. Gaillard, M. D. Mabaye, N. Pannetier and J.-L. Renaud, *Tetrahedron*, 2013, **69**, 4875–4882.

[10] C.-T. Yang, Z.-Q. Zhang, Y.-C. Liu and L. Liu, *Angew. Chem. Int. Ed*., 2011, **50**, 3904–3907.

[11] G. Sorin, R. M. Mallorquin, Y. Contie, A. Baralle, M. Malacria, J.-P. Goddard and L. Fensterbank, *Angew. Chem. Int. Ed*., 2010, **49**, 8721–8723.

[12] W. Ou, X. Xiang, R. Zou, Q. Xu, K. P. Loh and C. Su, *Angew. Chem. Int. Ed*., 2021, **60**, 6357–6361.

[13] D. Yu., W.-P. To, G. S. M. Tong, L.-L. Wu, K.-T. Chan, L. Du, D. L. Phillips, Y. Liu and C.-M. Che, *Chem. Sci.*, 2020, **11**, 6370–6382.

[14] K. Coetzee, C. E. Strasser, S. Cronje and H. G. Raubenheimer, *Z Naturforsch B.*, 2009, **64b**, 1449–1457.

[15] R. Mazurkiewicz, T. Gorewoda, A. Kuznik and M. Grymel, *Tetrahedron Lett.,* 2006, **47**, 4219–4220.

[16] M. S. M. Pearson and D. R. Carbery, *J. Org. Chem.,* 2009, **74**, 5320–5325.

[17] S. Nomura, K. Endo-Umeda, A. Aoyama, M. Makishima, Y. Hashimoto and M. Ishikawa, *ACS Med. Chem. Lett.* 2015, **6**, 902-907.

[18] K. Motoshima, M. Ishikawa, Y. Hashimoto and K. Sugita, *Bioorg. Med. Chem*., 2011, **19**, 3156-3172.

[19] S. C. Dakdouki, D. Villamin and N. Bar, *Eur. J. Org. Chem.,* 2010, **2**, 333-337.