

Efficient and Recyclable Dendritic Buchwald-type Ligand Catalyst for the Suzuki Reaction

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- SUPPORTING INFORMATION (15 Pages) -

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I- General: All reactions were carried out under an atmosphere of nitrogen by means of conventional Schlenk techniques, in oven-dried glassware. THF was distilled under nitrogen from sodium/benzophenone. Copper iodide (CuI), potassium iodide, 2-bromophenyl-boronic acid, tetrakis(triphenylphosphine)-palladium(0), palladium acetate, and *n*-butyllithium, were purchased from Aldrich Chemical Co. and were used without further purification. Dicyclohexylchloro-phosphine was purchased from Strem Chemical Co. NMR spectra were recorded on a Bruker-AC 200 spectrometer (^1H , 200 MHz, ^{13}C ; 50.3 MHz), or a Bruker-AC 250 spectrometer (^1H , 250 MHz; ^{13}C , 62.9 MHz), or a Bruker-AC 300 spectrometer (^1H , 300 MHz; ^{13}C , 75.5 MHz ^{31}P , 121.4 MHz). Chemicals shifts are reported in parts per million (δ) calibrated using referenced solvent signals. Mass spectroscopic measurements (MALDI-TOF) were performed at the CESAMO, University of Bordeaux 1. The elemental analyses were carried out in the analysis laboratory of the elemental analysis department at CNRS-Vernaison, France. GC spectra were recorded with a HP5890 series II gas chromatograph equipped with a fused silica capillary column heated gradually at 250°C (from 40°C, rate 15°C/min), vector gas: He; or with a Varian star 3400 gas chromatograph equipped with a fused silica column heated gradually at 220°C (from 40°C, rate 10°C/min), vector gas: N₂. Column head pressure: 5 or 10 psi. Detector: FID. Yields were calculated by a integration of product peaks (BORWIN 1.10) or (Star chromatography workstation 5.50) after determination of the response coefficient of each product vs. each chloroarene reagent. For each analysis, a sample of the THF phase of the reaction mixture was diluted in CH₂Cl₂ (2 mL) before injection.

Hexakis(4-iodophenyl-ethyl)benzene 4 :

Hexakis(4-bromophenyl-ethyl)benzene **3** (500 mg, 0.4 mmol), KI (23 g, 138 mmol), CuI (13 g, 68 mmol), were dissolved in DMF (100 mL). The mixture was maintained under nitrogen and stirred at reflux during 4 days. The solvent was then removed under vacuum and the brownish mixture was treated with H₂O (50 mL) and CH₂Cl₂ (50 mL). After filtration of the excess of salts by filtration over Celite, the product was extracted with CH₂Cl₂ (3x50 mL). Organic layers were gathered and dried over Na₂SO₄, then removal of the solvent purification of the residual oil by column chromatography on silica gel (oleum/CH₂Cl₂ = 1/4 as eluant) gave hexakis(4-iodophenyl-ethyl)benzene **4** as a white solid (54% yield). ^1H NMR (300 MHz, CDCl₃) δ : 3.11 (2H, m), 3.29 (2H, m), 7.93 (1H, m), 7.63 (1H, m), 7.55 (1H, m), 7.25 (1H,

m). ^{13}C NMR (75.5 MHz, CDCl_3) δ : 33.2 (CH_2 , d), 38.3 (CH_2 , d), 91.9 (C-I, Cq, s), 126.7 (CH, s), 129.1 (CH, d), 130.6 (CH, s), 137.1 (Cq, d), 138.0 (CH, s), 142.4 (Cq, d). MS-MALDI Calcd for $\text{C}_{54}\text{H}_{48}\text{I}_6$ ($[\text{M}+\text{Ag}]^+$): 1566.71; Found 1566.59.

Hexakis(2-bromobiphenylethyl)benzene 5 :

$\text{Pd}(\text{PPh}_3)_4$ (100 mg, 87.10^{-3} mmol) and hexakis(4-iodophenyl-ethyl)benzene **4** (700 mg, 0.5 mmol) were dissolved in THF (20 mL) under inert atmosphere. Then, a THF/ H_2O (2/1) (20 mL) solution of K_2CO_3 (1.2 g, 8.7 mmol) and 2-bromophenylboronic acid (870 mg, 4.35 mmol) were added, and the reaction medium was stirred under nitrogen, at 25°C for 2 days. The solvent was removed under vacuum, H_2O (50 mL) was added and the product was extracted with CH_2Cl_2 (3x50 mL). Organic layers were gathered and dried over Na_2SO_4 . After removal of the solvent, a yellow-brown oil which was obtained and purified by column chromatography on silica gel (oleum/ CH_2Cl_2 = 1/4 as eluant) to afford hexakis(2-bromobiphenylethyl)benzene **5** (70% yield) as a white solid. ^1H NMR (300 MHz, CDCl_3) δ : 3.17 (2H, m), 3.32 (2H, m), 7.32 (1H, d), 7.50-7.57 (6H, m), 7.80-7.82 (1H, d). ^{13}C NMR (75.5 MHz, CDCl_3) δ : 32.8 (CH_2 , d), 37.8 (CH_2 , d), 122.9 (Cq-Br, s), 126.4 (CH, s), 127.6 (CH, s), 128.1 (CH, s), 128.4 (CH, s), 128.9 (CH, s), 129.9 (CH, s), 131.6 (CH, s), 133.3 (CH, s), 136.9 (Cq, m), 139.2 (Cq, m), 141.7 (Cq), 142.4-142.6 (Cq). MS-MALDI Calcd for $\text{C}_{90}\text{H}_{72}\text{Br}_6$ ($[\text{M}+\text{Ag}]^+$): 1740.97; Found 1740.82.

Hexakis(2-bicyclohexylphosphino-biphenylethyl)benzene 6 :

Hexakis(2-bromobiphenylethyl)benzene **5** (300 mg, 0.2 mmol) was dissolved in THF (10 mL) under nitrogen and cooled to -78°C , *n*-butyllithium (2.5M in hexane) (0.5 mL, 1.2 mmol) was then added dropwise under stirring. The resulting yellowish solution was stirred at -78°C for 3-4h, and a yellow precipitate appeared. A solution of dicyclohexylchlorophosphine (0.3 mL, 1.4 mmol) in THF (3 mL) was added dropwise over 30 min to the reaction mixture at -78°C . The solution was then warmed up slowly to RT overnight. The reaction was quenched with a saturated NH_4Cl solution and extracted with ether (3x50 mL). The combined organic layers were dried over Na_2SO_4 and filtered. Removal of the solvent to gave a colorless oil which was precipitated with methanol under inert atmosphere to give **6** as white precipitate, 62% yield. ^1H NMR (300 MHz, CDCl_3) δ : 1.33-1.45 (11H, m, Cy), 1.83 (11H, m, Cy), 3.21

(2H, m), 3.40 (2H, m), 7.52 (7H, m), 7.80 (1H, m). ^{13}C NMR (75.5 MHz, CDCl_3) δ : 26.2 (CH₂, m), 27.0 (CH₂, m), 29.0 (CH₂, m), 30.0-30.4 (CH₂, m), 32.7 (CH₂, m), 34.4-34.7 (CH₂, d), 37.6-37.8 (CH₂, m), 126.0-126.6 (CH, m), 127.0-127.4 (CH, m), 128.4 (CH, s), 128.9 (CH, s), 128.1-128.6 (CH, s), 130.4-130.7 (CH, m), 132.2-132.7 (CH, m), 136.6 (Cq, s), 139.2 (Cq, m), 140.9-140.3 (Cq, m), 142.2 (Cq, s). (observed complexity due to P-C splitting). ^{31}P NMR (121.4 MHz, CDCl_3) δ : -13.1 (PCy₂, s). MS-MALDI Calcd for C₁₆₂H₂₀₄P₆O₆ ([M+Na]⁺): 2454.40; Found 2455.43 (the compound was found in its oxidized form due to the MS-MALDI experimental procedure).

2- Recovery/Re-Use experiments by addition of substrates :

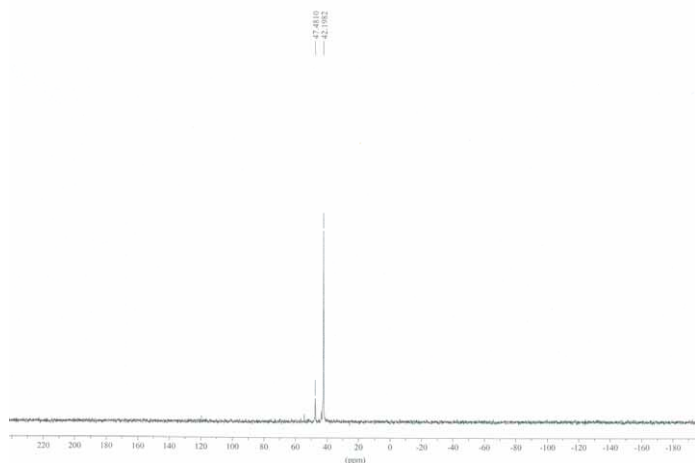
In a typical recycling/re-use procedure, the reaction proceeds with 1.0 equiv. *o*-chlorotoluene, 1.5 equiv boronic acid, 3.0 equiv K₃PO₄, cat. Pd(OAc)₂ (3 mol%), cat. hexaphosphine ligand **6** (0.5 mol%), L: Pd = 1:1, THF/H₂O (1/1) (10 mL/mmol of halide), 83°C. After the reaction was completed, substrates were added again to the reaction mixture. Yields remained quantitative until the fourth cycle. Then, the reactivity regularly decreased to 50 % yield for the sixth cycle.

Deleted: Subsequently, a demixion

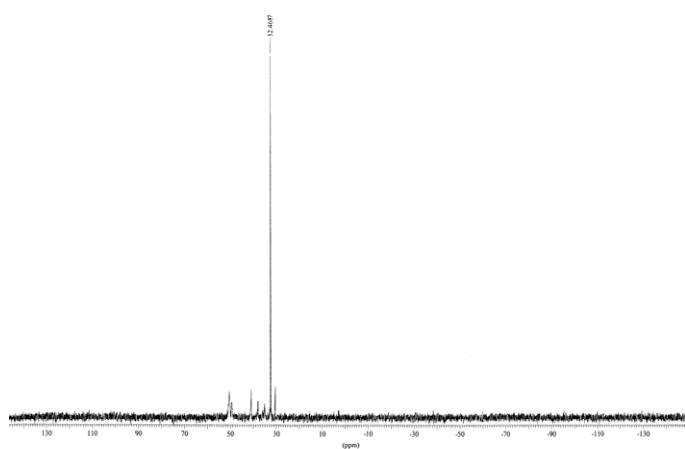
3- Analysis of the catalyst :

In both procedure of recovery/re-use of the catalyst, after the catalyst has died, ^{31}P NMR spectrum showed several peaks, δ from 27 to 48 ppm (see spectra below). The ^1H and ^{13}C NMR spectrum shows the signal of the catalyst with the presence of large amount of aromatic signals of borate salts species. Indeed, the mass of the precipitate is three times that of the initially loaded catalyst.

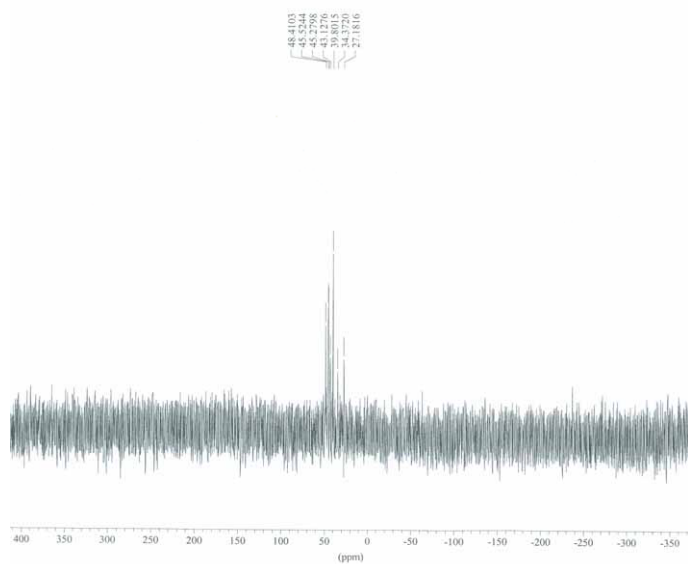
Below is the ^{31}P NMR of Hexphosphine ligand **6** and Pd(OAc)₂ in CDCl_3 : cat. Hexaphosphine ligand **6** (0.16 eq.), cat. Pd(OAc)₂ (1.0 eq.), i.e. L: Pd = 1:1



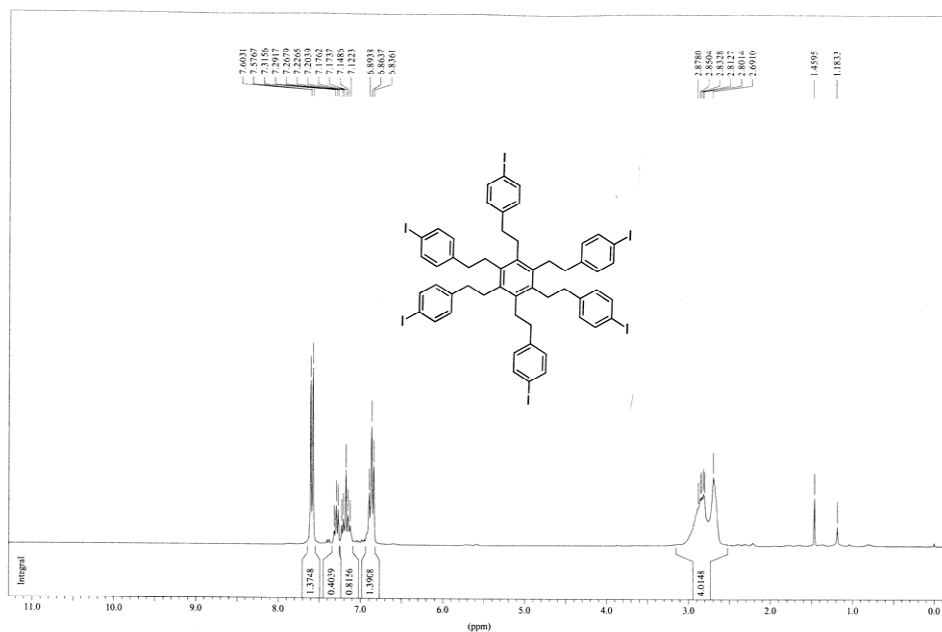
Below is the ^{31}P NMR of the died catalyst after recovery/re-use by precipitation after the fourth cycle :



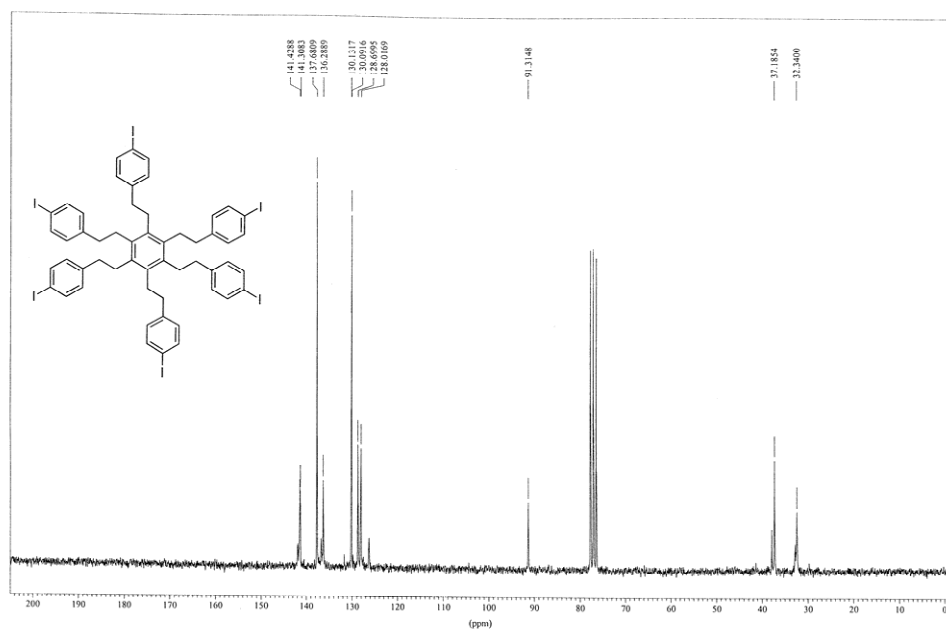
Below is the ^{31}P NMR of the died catalyst after recovery/re-use by addition of substrates after the sixth cycle :



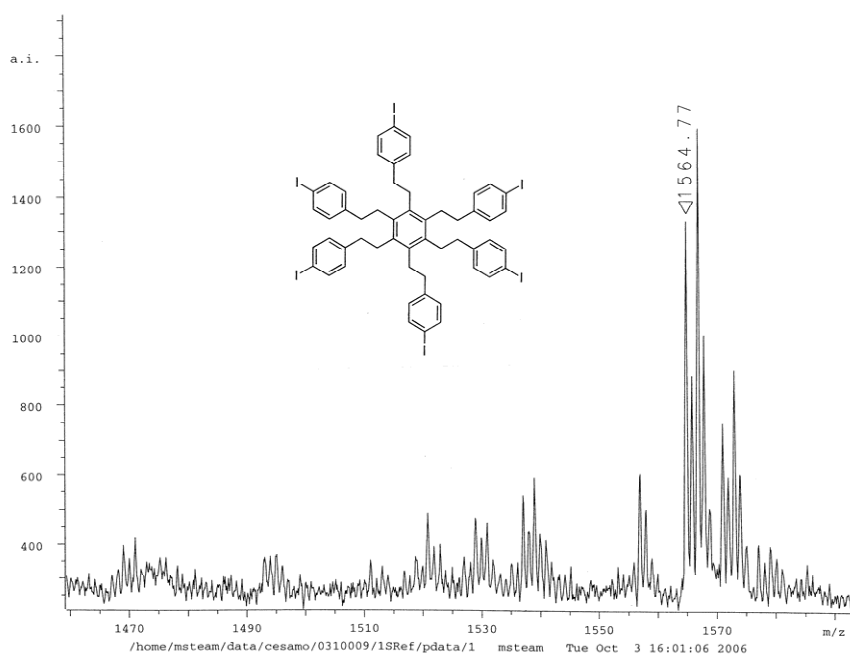
^1H NMR spectrum of **4**



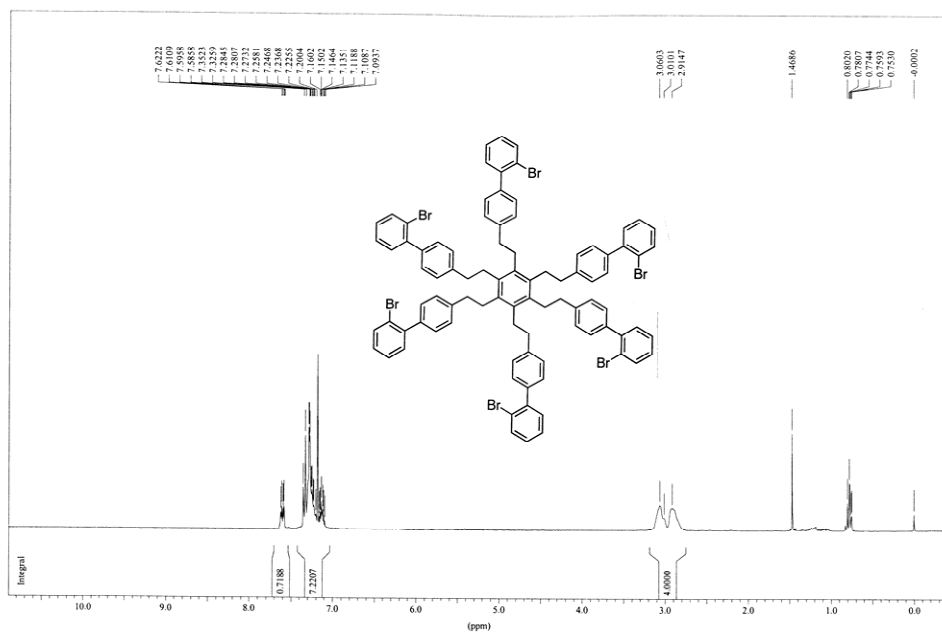
^{13}C NMR spectrum of **4**



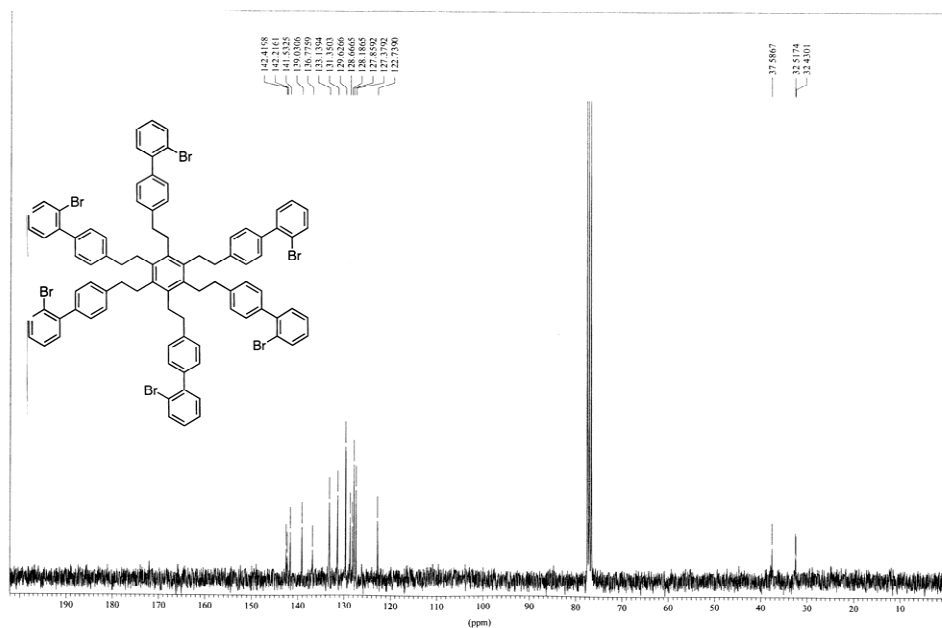
MS-MALDI of 4



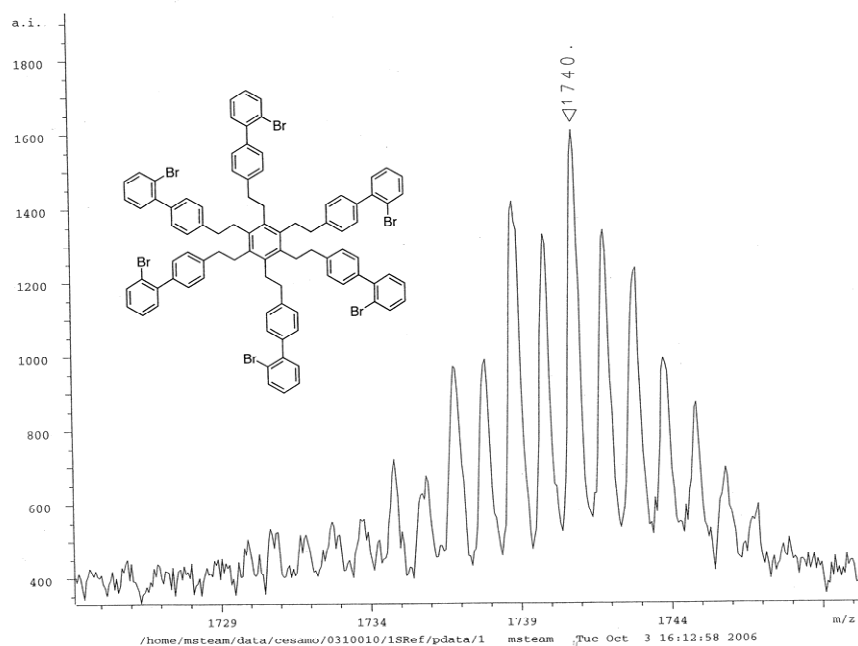
^1H NMR spectrum of **5**



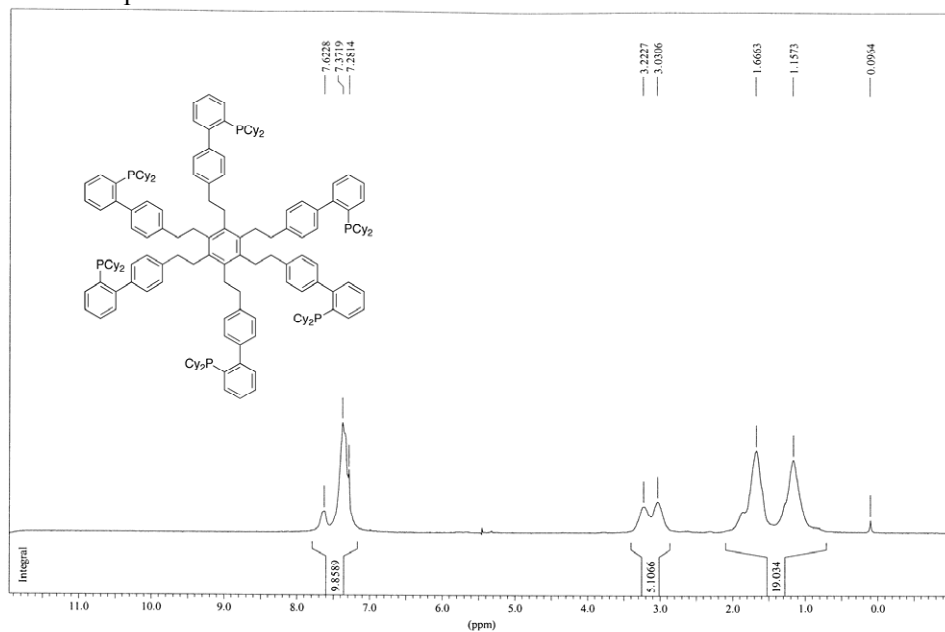
^{13}C NMR spectrum of **5**



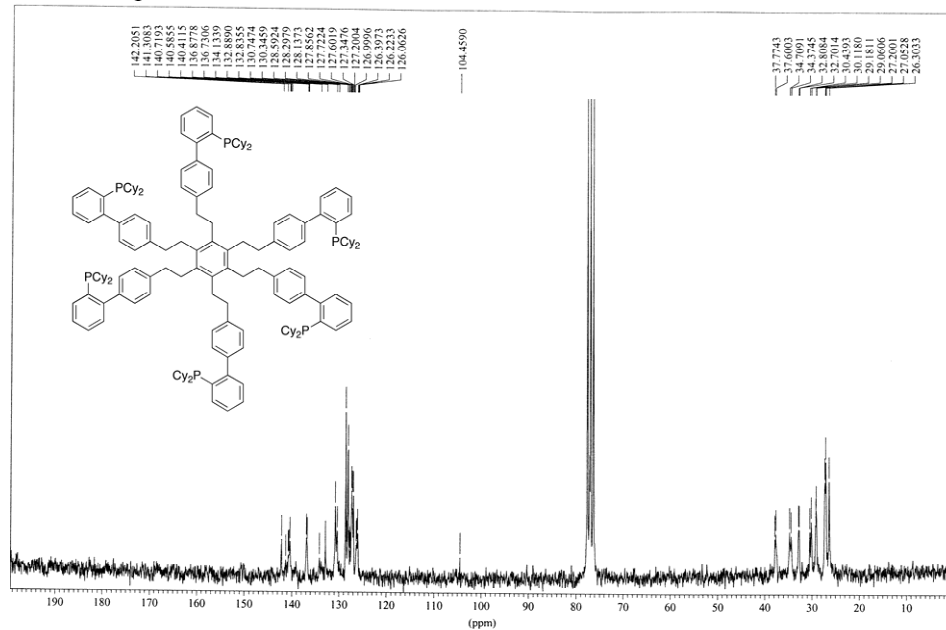
MS-MALDI spectrum of **5**



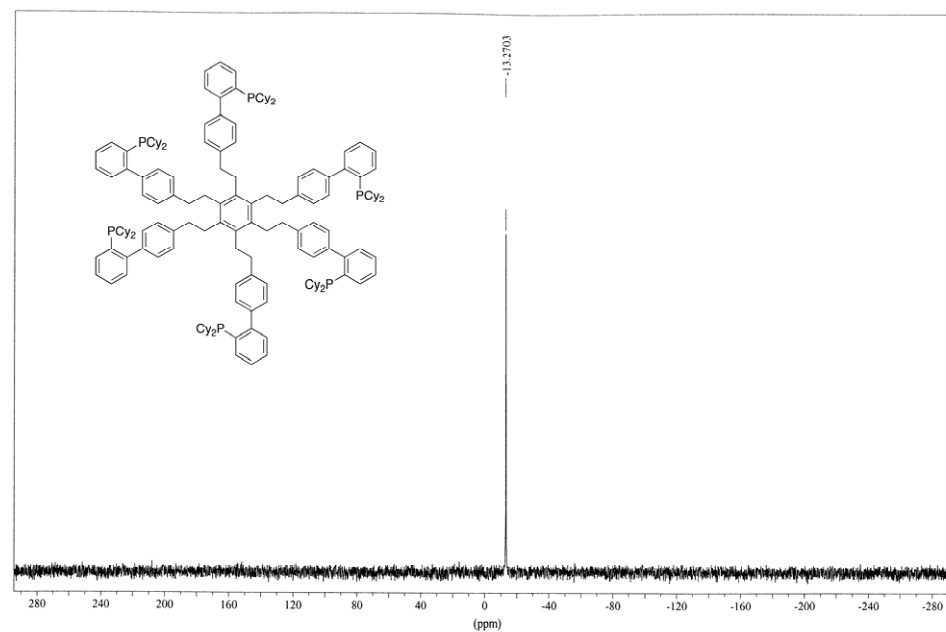
^1H NMR spectrum of **6**



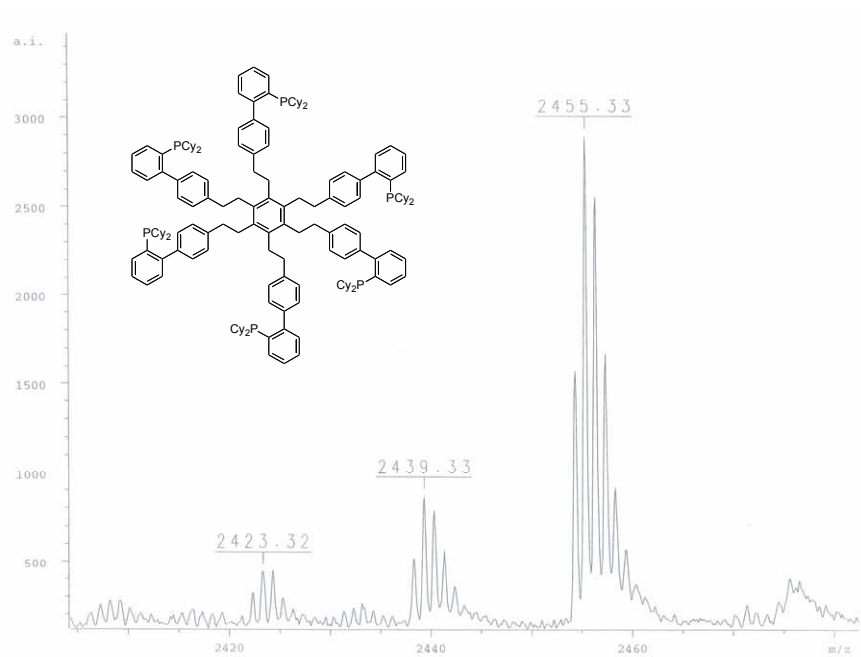
^{13}C NMR spectrum of **6**



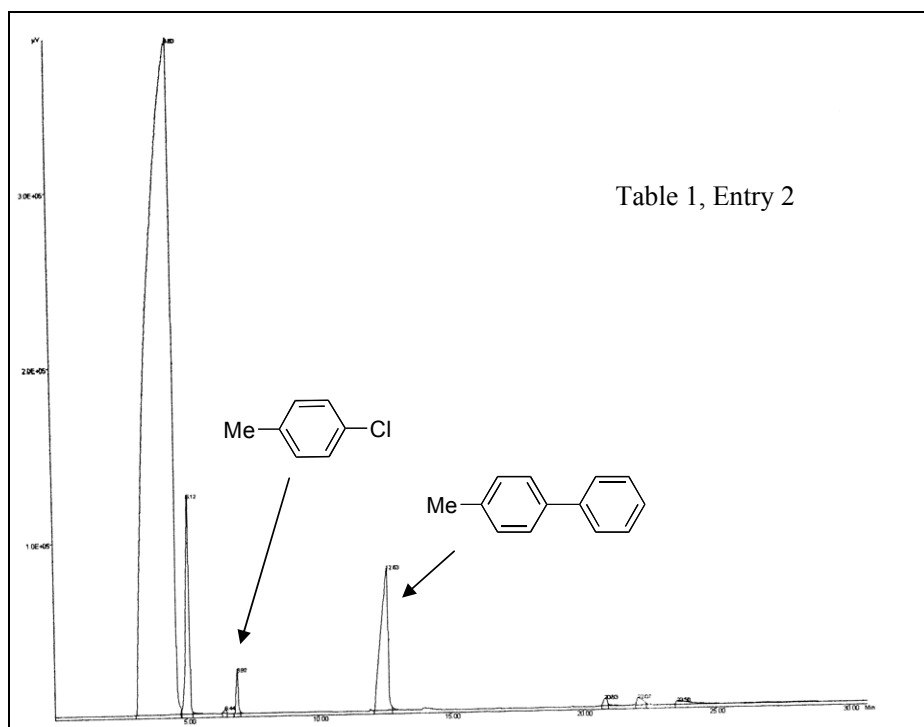
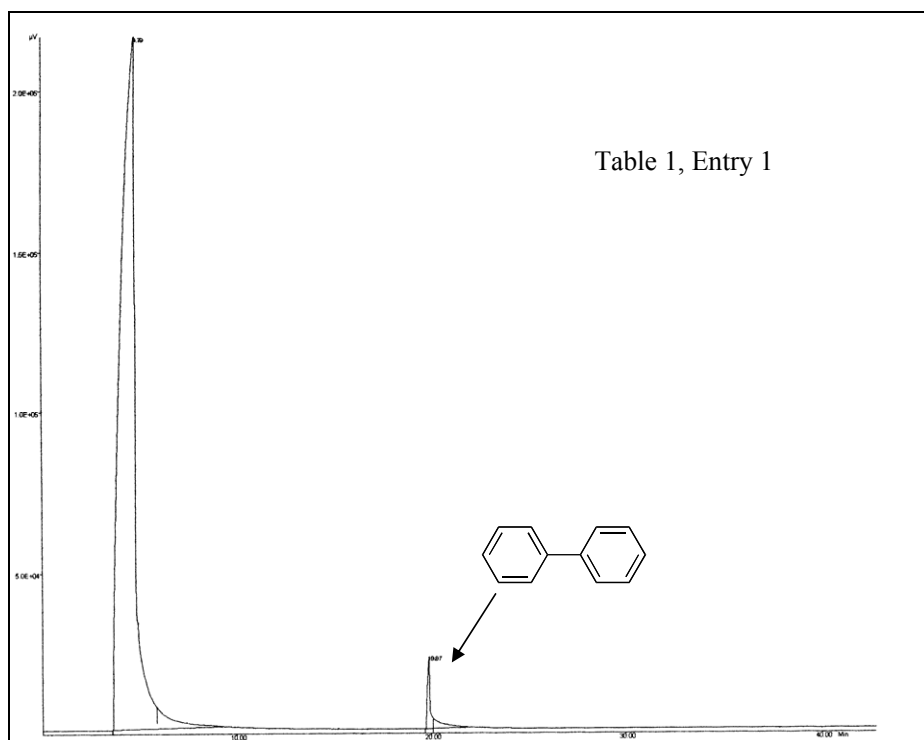
^{31}P NMR spectrum of **6**

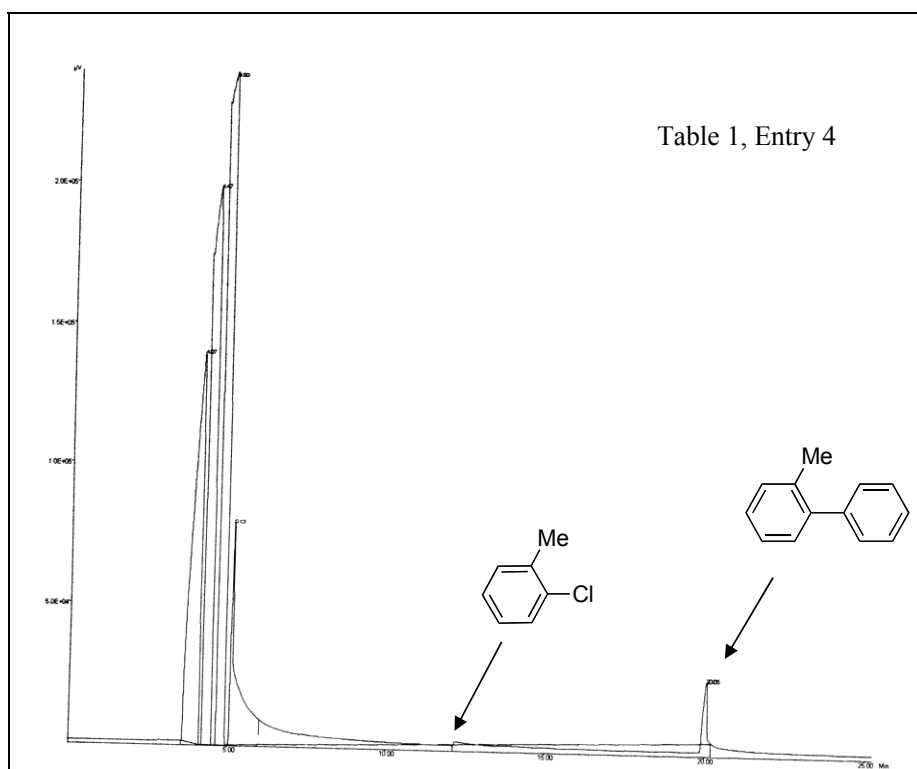
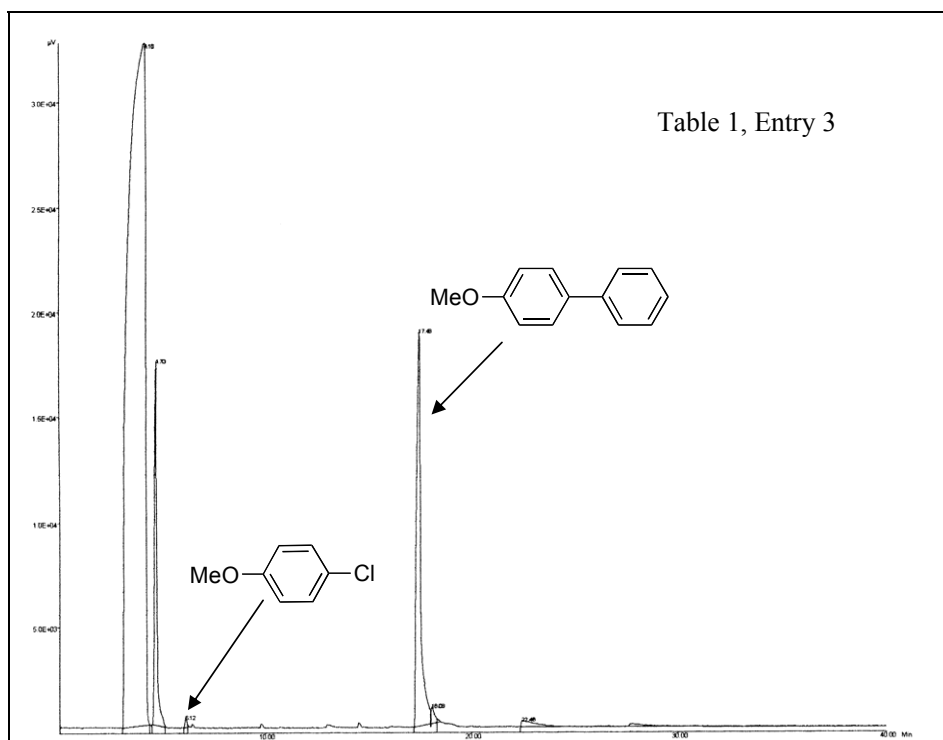


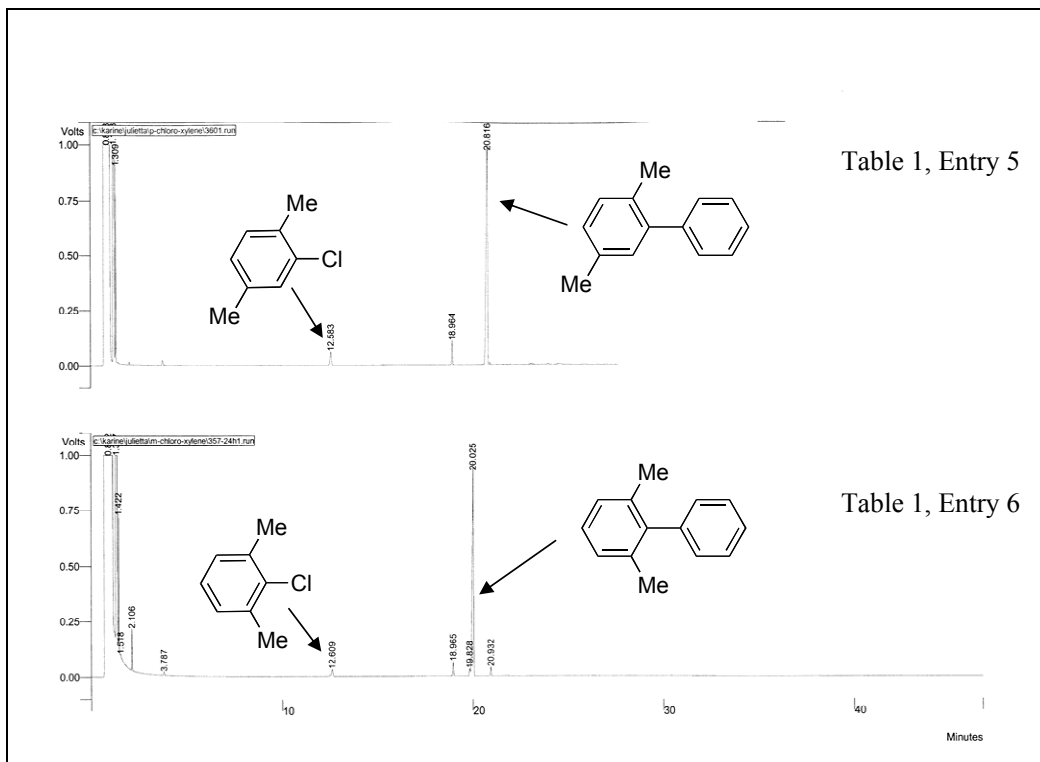
MS-MALDI spectrum of **6**



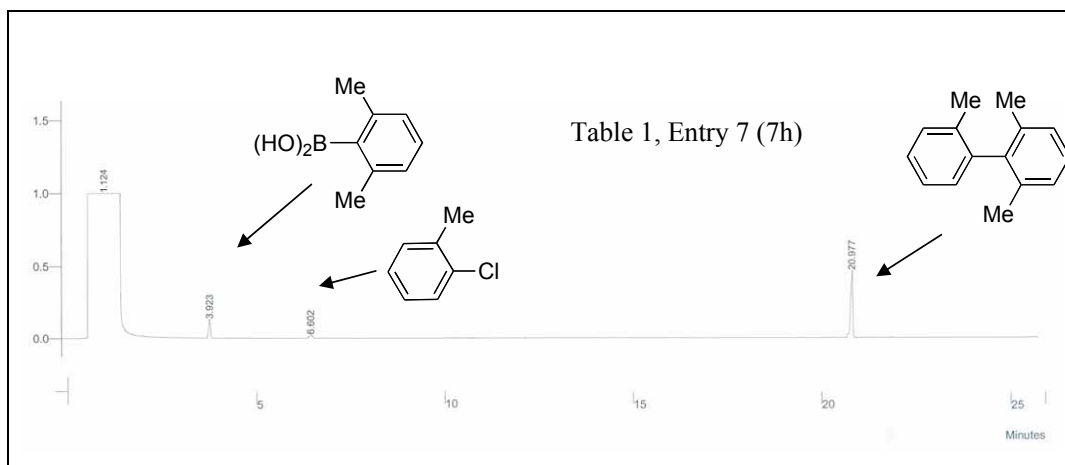
GC spectra of reactions in Table 1



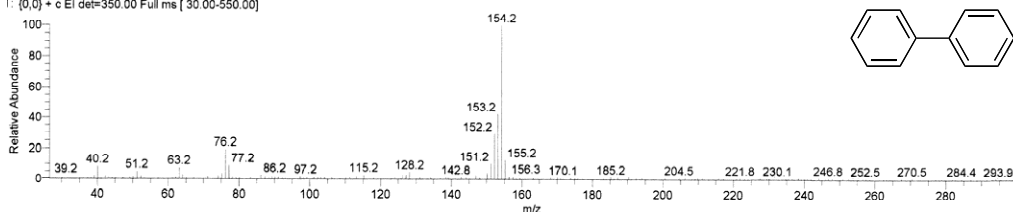




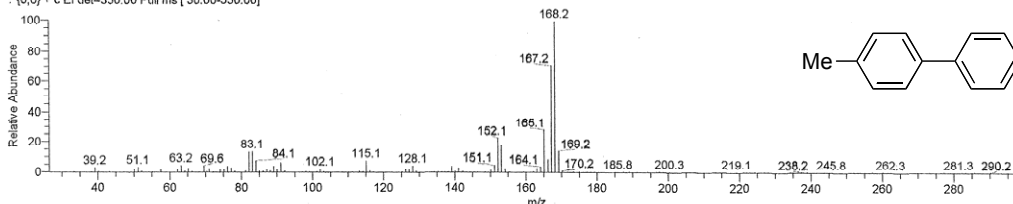
MS spectra of compounds in Table 1:



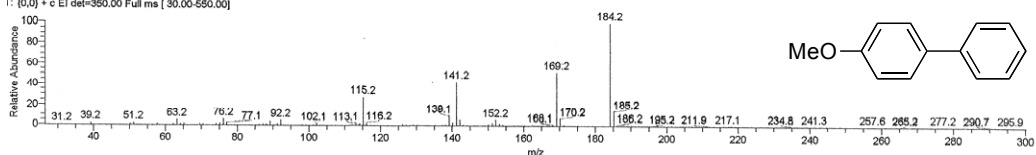
IL_364#1351-1355 RT: 12.30-12.33 AV: 5 SB: 1 12.23 NL: 5.80E3
T: (0,0) + c EI det=350.00 Full ms [30.00-550.00]



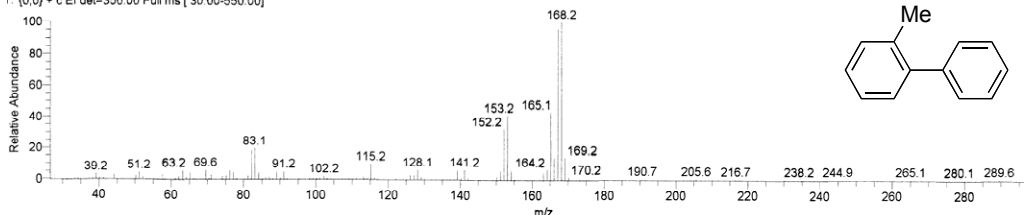
L_2_20_02_07#1654-1659 RT: 15.14-15.18 AV: 6 SB: 2 15.09, 15.23 NL: 4.61E4
T: (0,0) + c EI det=350.00 Full ms [30.00-550.00]



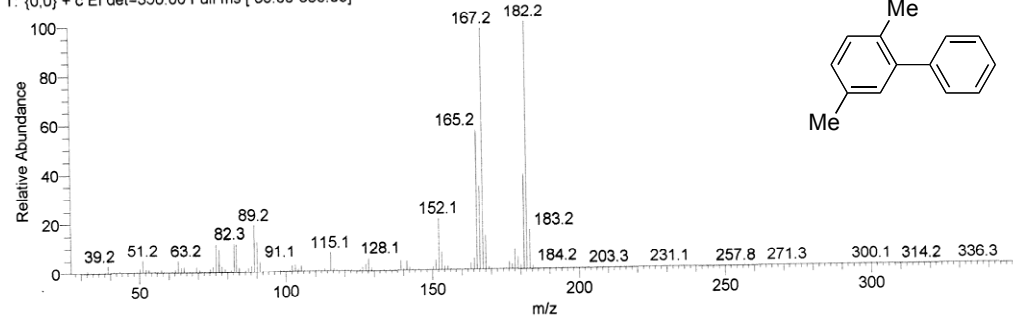
IL_1_20_02_07#2149-2156 RT: 19.04-19.10 AV: 8 SB: 2 18.83, 19.23 NL: 1.83E6
T: (0,0) + c EI det=350.00 Full ms [30.00-550.00]



IL_364#1418-1424 RT: 12.86-12.91 AV: 7 SB: 1 12.71 NL: 2.51E4
T: (0,0) + c EI det=350.00 Full ms [30.00-550.00]



IL_360#1724-1730 RT: 15.40-15.45 AV: 7 SB: 2 15.20, 15.68 NL: 3.64E4
T: (0,0) + c EI det=350.00 Full ms [30.00-550.00]



J1357#1528-1534 RT: 13.90-13.95 AV: 7 SB: 1 13.70 NL: 1.63E4
T: {0,0} + c EI det=350.00 Full ms [30.00-550.00]

