Copper-catalyzed asymmetric addition of arylboronates to isatins: A catalytic cycle involving alkoxocopper intermediates

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Electronic Supplementary Information

I. General

All air- and moisture-sensitive manipulations were carried out with standard Schlenk techniques under nitrogen or in a glove box under argon.

THF, toluene, and dioxane were purified by passing through neutral alumina columns under nitrogen. DMF was distilled over CaH_2 under vacuum. CH_2Cl_2 was distilled over CaH_2 under nitrogen. Hexane was distilled over benzophenone ketyl under nitrogen.

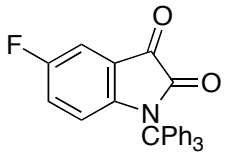
5-Fluoroisatin (Wako Chemicals), 5-methylisatin (ICN), 6-bromoisatin (Wako Chemicals), 6-chloroisatin (Wako Chemicals), isatin (Wako Chemicals), triphenylmethyl bromide (TCI), ethyl chloroglyoxylate (TCI), 2,6-dimethylaniline (Wako Chemicals), aniline (Wako Chemicals), 2,6-diethylaniline (Wako Chemicals), 2,6-diisopropylaniline (TCI), pyridine (Wako Chemicals), (*S*)-phenylglycinol (Wako Chemicals), (*S*)-valinol (TCI), (*S*)-*tert*-leucinol (Aldrich), trimethyl orthoformate (Wako Chemicals), trimethylsilyl-diazomethane (Nacalai Tesque; 10 wt% in hexane), triethylsilane (ShinEtsu), trifluoroacetic acid (Wako Chemicals), KO*t*-Bu (Wako Chemicals), NaH (Kanto Chemicals; 60 wt% in mineral oil), $LiAlH_4$ (Kanto Chemicals), HCl (TCI; 1.0 M solution in Et_2O), KPF_6 (Aldrich), and HBF_4*aq* (Wako Chemicals; 42 wt%) were used as received. CuCl (Kanto Chemicals) was washed with HCl*aq* and dried under vacuum prior to use.

Arylboronic acid neopentylglycol esters **2**,[1] CuO*t*-Bu(IPr),[2] and (*R*,*R*)-**7**[3] were synthesized following the literature procedures.

All other chemicals and solvents were purchased from Aldrich, Wako Chemicals, TCI, or Kanto Chemicals and used as received.

II. Synthesis of Substrates and Ligand Salts

5-Fluoro-1-tritylisatin (1a)



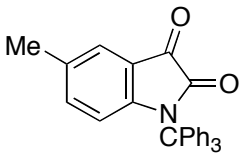
NaH (356 mg, 8.90 mmol; 60 wt% in mineral oil) was added portionwise to a solution of 5-fluoroisatin (1.32 g, 8.01 mmol) in DMF (8.0 mL), and the resulting mixture was stirred for 30 min at room temperature. Triphenylmethyl bromide (2.84 g, 8.78 mmol) was added to it

[1] H. Chaumeil, S. Signorella and C. Le Drian, *Tetrahedron* 2000, **56**, 9655.
[2] N. P. Mankad, D. S. Laitar and J. P. Sadighi, *Organometallics* 2004, **23**, 3369.
[3] T. J. Seiders, D. W. Ward and R. H. Grubbs, *Org. Lett.* 2001, **3**, 3225.

with additional DMF (2.0 mL), and the mixture was stirred for 2.5 h at room temperature. The reaction mixture was diluted with $CHCl_3$ and washed with saturated NaCl*aq*. The organic layer was dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with $CHCl_3$/EtOAc/hexane = 1/1/6, and the solid thus obtained was recrystallized from CH_2Cl_2/hexane to afford 5-fluoro-1-tritylisatin (2.72 g, 6.68 mmol; 83% yield) as an orange solid.

^{1}H NMR ($CDCl_3$): δ 7.42 (d, $^3J_{HH}$ = 7.2 Hz, 6H), 7.31-7.23 (m, 10H), 6.91 (td, ^3J = 8.7 Hz and $^4J_{HH}$ = 2.9 Hz, 1H), 6.35 (dd, $^3J_{HH}$ = 8.9 Hz and $^4J_{HF}$ = 3.7 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 182.5 (d, $^4J_{CF}$ = 2.1 Hz), 159.2 (d, $^5J_{CF}$ = 2.1 Hz), 158.8 (d, $^1J_{CF}$ = 247 Hz), 148.4 (d, $^4J_{CF}$ = 2.1 Hz), 141.0, 129.3, 128.1, 127.6, 123.3 (d, $^2J_{CF}$ = 23.8 Hz), 119.9 (d, $^3J_{CF}$ = 6.2 Hz), 119.0 (d, $^3J_{CF}$ = 7.2 Hz), 111.3 (d, $^2J_{CF}$ = 23.8 Hz), 75.7. Anal. Calcd for $C_{27}H_{18}FNO_2$: C, 79.59; H, 4.45. Found: C, 79.70; H, 4.35.

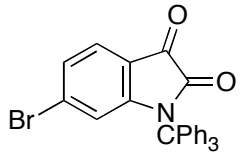
5-Methyl-1-tritylisatin (1b)



This was synthesized from 5-methylisatin, following the procedure for compound **1a**. Orange solid. 72% yield.

^{1}H NMR ($CDCl_3$): δ 7.44 (d, $^3J_{HH}$ = 7.0 Hz, 6H), 7.39 (dd, $^4J_{HH}$ = 1.3 Hz and $^5J_{HH}$ = 0.6 Hz, 1H), 7.27 (t, $^3J_{HH}$ = 7.0 Hz, 6H), 7.23 (tt, $^3J_{HH}$ = 7.3 Hz and $^4J_{HH}$ = 1.3 Hz, 3H), 6.99 (dd, $^3J_{HH}$ = 8.4 Hz and $^4J_{HH}$ = 1.6 Hz, 1H), 6.25 (d, $^3J_{HH}$ = 8.3 Hz, 1H), 2.23 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 183.2, 159.6, 150.1, 141.3, 137.4, 133.1, 129.3, 128.0, 127.4, 125.0, 119.2, 117.5, 75.4, 20.4. Anal. Calcd for $C_{28}H_{21}NO_2$: C, 83.35; H, 5.25. Found: C, 83.14; H, 5.30.

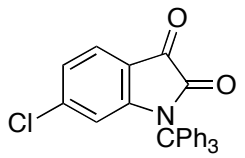
6-Bromo-1-tritylisatin (1c)



This was synthesized from 6-bromoisatin, following the procedure for compound **1a**. Yellow solid. 78% yield.

^{1}H NMR ($CDCl_3$): δ 7.45-7.40 (m, 7H), 7.30 (t, $^3J_{HH}$ = 6.9 Hz, 6H), 7.26 (tt, $^3J_{HH}$ = 6.9 Hz and $^4J_{HH}$ = 1.3 Hz, 3H), 7.16 (dd, $^3J_{HH}$ = 7.9 Hz and $^4J_{HH}$ = 1.4 Hz, 1H), 6.46 (d, $^4J_{HH}$ = 1.3 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 181.8, 159.2, 153.0, 140.8, 132.1, 129.3, 128.2, 127.7, 126.7, 125.6, 121.0, 117.9, 75.9. Anal. Calcd for $C_{27}H_{18}BrNO_2$: C, 69.24; H, 3.87. Found: C, 69.27; H, 3.86.

6-Chloro-1-tritylisatin (1d)

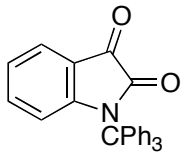


This was synthesized from 6-chloroisatin, following the procedure for compound **1a**. Yellow solid. 70% yield.

^{1}H NMR ($CDCl_3$): δ 7.52 (d, $^3J_{HH}$ = 8.0 Hz, 1H), 7.42 (d, $^3J_{HH}$ = 7.3 Hz, 6H), 7.30 (t, $^3J_{HH}$

= 7.3 Hz, 6H), 7.26 (tt, $^3J_{HH}$ = 7.1 Hz and $^4J_{HH}$ = 1.3 Hz, 3H), 6.99 (dd, $^3J_{HH}$ = 8.0 Hz and $^4J_{HH}$ = 1.6 Hz, 1H), 6.31 (d, $^3J_{HH}$ = 1.6 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 181.5, 159.3, 153.2, 143.2, 140.8, 129.3, 128.2, 127.7, 125.7, 123.7, 118.1, 117.5, 75.8. Anal. Calcd for $C_{27}H_{18}ClNO_2$: C, 76.50; H, 4.28. Found: C, 76.50; H, 4.24.

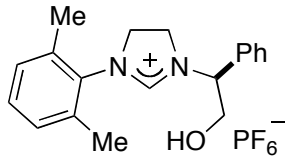
1-Tritylisatin (1e; CAS 41128-14-7)



This was synthesized from isatin, following the procedure for compound **1a**. Yellow solid. 94% yield.

^{1}H NMR ($CDCl_3$): δ 7.59 (dd, $^3J_{HH}$ = 7.6 Hz and $^4J_{HH}$ = 1.6 Hz, 1H), 7.44 (d, $^3J_{HH}$ = 7.2 Hz, 6H), 7.28 (t, $^3J_{HH}$ = 7.4 Hz, 6H), 7.23 (t, $^3J_{HH}$ = 7.3 Hz, 3H), 7.19 (ddd, $^3J_{HH}$ = 8.2 and 7.5 Hz and and $^4J_{HH}$ = 1.1 Hz, 1H), 6.99 (t, $^3J_{HH}$ = 7.4 Hz, 1H), 6.38 (d, $^3J_{HH}$ = 8.3 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 183.0, 159.4, 152.2, 141.2, 136.8, 129.3, 128.0, 127.4, 124.7, 123.3, 119.1 117.7, 75.5.

(*S*)-8a[4]



Ethyl chloroglyoxylate (2.47 mL, 22.0 mmol) was added dropwise to a solution of 2,6-dimethylaniline (2.42 g, 20.0 mmol) and pyridine (1.77 mL, 22.0 mmol) in CH_2Cl_2 (20 mL) at 0 °C, and the resulting solution was stirred for 12 h at room temperature. The reaction mixture was diluted with EtOAc and washed successively with 1 M HCl*aq*, saturated $NaHCO_3$*aq*, and saturated NaCl*aq*. The organic layer was dried over $MgSO_4$, filtered, and concentrated under vacuum to afford ethyl 2,6-dimethylphenyloxamate as a pale pink solid (4.29 g, 19.4 mmol; 97% yield).

^{1}H NMR ($CDCl_3$): δ 8.40 (bs, 1H), 7.15 (dd, $^3J_{HH}$ = 8.6 and 6.3 Hz, 1H), 7.10 (d, $^3J_{HH}$ = 7.4 Hz, 2H), 4.43 (q, $^3J_{HH}$ = 7.2 Hz, 2H), 2.24 (s, 6H), 1.44 (t, $^3J_{HH}$ = 7.1 Hz, 3H).

A solution of ethyl 2,6-dimethylphenyloxamate (664 mg, 3.00 mmol) and (*S*)-phenylglycinol (454 mg, 3.31 mmol) in CH_2Cl_2 (8.0 mL) was refluxed for 3 days. The reaction mixture was diluted with EtOAc and washed successively with 1 M HCl*aq* and saturated NaCl*aq*. The organic layer was dried over $MgSO_4$, filtered, and concentrated under vacuum to afford (*S*)-*N*-(2,6-dimethylphenyl)-*N'*-(2-hydroxy-1-phenylethyl)oxalamide as a white solid. This solid was added to a suspension of $LiAlH_4$ (456 mg, 12.0 mmol) in THF (8.0 mL) at 0 °C, and the mixture was stirred for 20 h at 70 °C. The reaction was cooled to 0 °C, and H_2O (0.4 mL), 15% NaOH*aq* (0.4 mL), and H_2O (1.2 mL) were slowly added to it. The precipitate that formed was removed by filtration through celite with THF. The filtrate was concentrated under vacuum to afford (*S*)-*N*-(2,6-dimethylphenyl)-*N'*-(2-hydroxy-1-phenylethyl)ethylenediamine as a pale yellow oil (853 mg, 3.00 mmol; 100% yield).

^{1}H NMR ($CDCl_3$): δ 7.37-7.33 (m, 2H), 7.30-7.27 (m, 3H), 6.98 (d, $^3J_{HH}$ = 7.4 Hz, 2H), 6.81 (t, $^3J_{HH}$ = 7.4 Hz, 1H), 3.79 (dd, $^3J_{HH}$ = 8.4 and 4.5 Hz, 1H), 3.73 (dd, $^2J_{HH}$ = 10.7 Hz

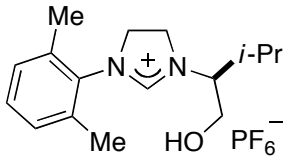
[4] H. Clavier, L. Coutable, L. Toupet, J.-C. Guillemin and M. Mauduit, *J. Organomet. Chem.* 2005, **690**, 5237.

and $^3J_{HH}$ = 4.5 Hz, 1H), 3.58 (dd, $^2J_{HH}$ = 10.7 Hz and $^3J_{HH}$ = 8.5 Hz, 1H), 3.15-3.03 (m, 2H), 2.79 (ddd, $^2J_{HH}$ = 12.1 Hz and $^3J_{HH}$ = 7.3 and 4.5 Hz, 1H), 2.71 (ddd, $^2J_{HH}$ = 12.0 Hz and $^3J_{HH}$ = 6.1 and 4.7 Hz, 1H), 2.28 (s, 6H).

HCl (3.0 mL, 3.0 mmol; 1.0 M solution in Et_2O) was added dropwise to a solution of (*S*)-*N*-(2,6-dimethylphenyl)-*N'*-(2-hydroxy-1-phenylethyl)ethylenediamine (853 mg, 3.00 mmol) in Et_2O (10 mL) and the mixture was stirred for 5 min at room temperature. This was then diluted with hexane and the resulting precipitate was collected by filtration. The solid thus obtained was dissolved in toluene (6.0 mL), and trimethyl orthoformate (1.42 mL, 13.0 mmol) was added to it. This mixture was stirred for 20 h at 90 °C, and the solvent was removed under vacuum. The residue was then dissolved in H_2O (20 mL) and washed with EtOAc. KPF_6 (1.11 g, 6.03 mmol) was added to the aqueous solution and the mixture was stirred for 12 h at room temperature. After extraction with CH_2Cl_2, the organic layer was dried over $MgSO_4$, filtered, and concentrated under vacuum. The resulting solid was redissolved in CH_2Cl_2 and diluted with hexane. The precipitate that formed was collected by filtration to afford compound (*S*)-**8a** as a white solid (689 mg, 1.56 mmol; 52% yield). $[\alpha]^{20}_D$ +24.5 (*c* 1.00, acetone).

^{1}H NMR (acetone-d_6): δ 8.90 (s, 1H), 7.57-7.54 (m, 2H), 7.52-7.44 (m, 3H), 7.34 (t, $^3J_{HH}$ = 7.5 Hz, 1H), 7.26 (d, $^3J_{HH}$ = 7.6 Hz, 2H), 5.17 (dd, $^3J_{HH}$ = 9.3 and 4.2 Hz, 1H), 4.82 (bs, 1H), 4.51-4.43 (m, 2H), 4.42-4.25 (m, 3H), 4.19 (ddd, $^2J_{HH}$ = 11.6 Hz and $^3J_{HH}$ = 6.3 and 3.9 Hz, 1H), 2.41 (s, 6H). ^{13}C NMR (acetone-d_6): δ 159.8, 137.0, 135.1, 134.7, 131.0, 130.1, 130.03, 129.98, 128.7, 65.2, 61.9, 51.4, 48.6, 17.7. Anal. Calcd for $C_{19}H_{23}F_6N_2OP$: C, 51.82; H, 5.26. Found: C, 51.79; H, 5.17.

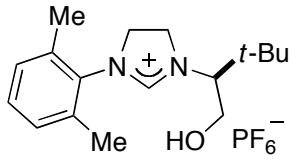
(*S*)-8b



This was synthesized from (*S*)-valinol and ethyl 2,6-dimethylphenyloxamate, following the procedure for compound (*S*)-**8a**. White solid. 34% yield. $[\alpha]^{20}_D$ –1.9 (*c* 1.00, acetone).

^{1}H NMR (acetone-d_6): δ 8.70 (s, 1H), 7.33 (t, $^3J_{HH}$ = 7.6 Hz, 1H), 7.25 (d, $^3J_{HH}$ = 7.7 Hz, 2H), 4.54-4.50 (m, 1H), 4.50-4.45 (m, 4H), 4.04-3.98 (m, 1H), 3.94-3.87 (m, 1H), 3.69 (ddd, $^2J_{HH}$ = 10.2 Hz and $^3J_{HH}$ = 8.2 and 3.8 Hz, 1H), 2.39 (s, 6H), 2.26-2.14 (m, 1H), 1.15 (d, $^3J_{HH}$ = 6.7 Hz, 3H), 1.07 (d, $^3J_{HH}$ = 6.6 Hz, 3H). ^{13}C NMR (acetone-d_6): δ 160.3, 137.0, 134.6, 130.9, 130.0, 68.2, 59.6, 51.3, 47.7, 28.0, 20.1, 19.3, 17.6. Anal. Calcd for $C_{16}H_{25}F_6N_2OP$: C, 47.29; H, 6.20. Found: C, 47.38; H, 6.19.

(*S*)-8c

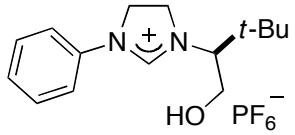


This was synthesized from (*S*)-*tert*-leucinol and ethyl 2,6-dimethylphenyloxamate, following the procedure for compound (*S*)-**8a**. White solid. 50% yield. $[\alpha]^{20}_D$ +11.3 (*c* 1.00, acetone).

^{1}H NMR (acetone-d_6): δ 8.73 (s, 1H), 7.33 (t, $^3J_{HH}$ = 7.6 Hz, 1H), 7.26 (d, $^3J_{HH}$ = 7.6 Hz, 2H), 4.61-4.45 (m, 5H), 4.10-4.05 (m, 1H), 3.99 (ddd, $^2J_{HH}$ = 11.7 Hz and $^3J_{HH}$ = 10.3 and 5.6

Hz, 1H), 3.80 (dd, $^3J_{HH}$ = 10.3 and 3.9 Hz, 1H), 2.38 (s, 6H), 1.15 (s, 9H). ^{13}C NMR (acetone-d_6): δ 161.2, 136.9, 134.5, 130.9, 130.0, 71.4, 58.0, 51.5, 49.9, 34.2, 27.5, 17.6. Anal. Calcd for $C_{17}H_{27}F_6N_2OP$: C, 48.57; H, 6.47. Found: C, 48.34; H, 6.41.

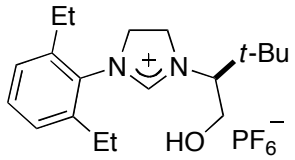
(*S*)-8d



This was synthesized from aniline and ethyl chloroglyoxylate, following the procedure for compound (*S*)-**8a**. White solid. 45% yield. $[\alpha]^{20}_D$ +8.0 (*c* 1.00, acetone).

^{1}H NMR (acetone-d_6): δ 9.21 (s, 1H), 7.54-7.47 (m, 4H), 7.36 (tt, $^3J_{HH}$ = 7.1 Hz and $^4J_{HH}$ = 1.3 Hz, 1H), 4.73-4.63 (m, 2H), 4.55-4.43 (m, 2H), 4.35 (t, $^3J_{HH}$ = 5.2 Hz, 1H), 4.08-3.99 (m, 2H), 3.84 (dd, $^3J_{HH}$ = 9.3 and 4.5 Hz, 1H), 1.14 (s, 9H). ^{13}C NMR (acetone-d_6): δ 156.5, 137.3, 130.8, 127.7, 118.8, 72.2, 58.3, 49.8, 49.3, 34.4, 27.5. Anal. Calcd for $C_{15}H_{23}F_6N_2OP$: C, 45.92; H, 5.91. Found: C, 45.66; H, 5.73.

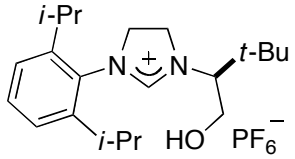
(*S*)-8e



This was synthesized from 2,6-diethylaniline and ethyl chloroglyoxylate, following the procedure for compound (*S*)-**8a**. White amorphous. 25% yield. $[\alpha]^{20}_D$ +7.5 (*c* 0.84, acetone).

^{1}H NMR (acetone-d_6): δ 8.75 (s, 1H), 7.45 (t, $^3J_{HH}$ = 7.7 Hz, 1H), 7.32 (d, $^3J_{HH}$ = 7.7 Hz, 2H), 4.62-4.45 (m, 5H), 4.06 (dt, $^2J_{HH}$ = 11.9 Hz and $^3J_{HH}$ = 4.0 Hz, 1H), 3.99 (ddd, $^2J_{HH}$ = 11.7 Hz and $^3J_{HH}$ = 11.0 and 5.7 Hz, 1H), 3.82 (dd, $^3J_{HH}$ = 10.4 and 4.0 Hz, 1H), 2.74 (q, $^3J_{HH}$ = 7.9 Hz, 2H), 2.72 (q, $^3J_{HH}$ = 7.9 Hz, 2H), 1.25 (t, $^3J_{HH}$ = 7.4 Hz, 3H), 1.24 (t, $^3J_{HH}$ = 7.6 Hz, 3H), 1.15 (s, 9H). ^{13}C NMR (acetone-d_6): δ 161.3, 142.94, 142.92, 133.1, 131.5, 128.30, 128.26, 71.5, 57.9, 53.0, 50.0, 34.3, 27.5, 24.6, 24.5, 15.6, 15.5. HRMS (ESI-TOF) calcd for $C_{19}H_{31}N_2O$ ($M–PF_6^-$) 303.2431, found 303.2430.

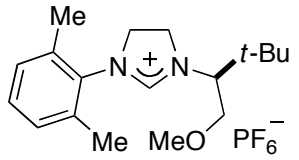
(*S*)-8f



This was synthesized from 2,6-diisopropylaniline and ethyl chloroglyoxylate, following the procedure for compound (*S*)-**8a**. Pale yellow solid. 17% yield. $[\alpha]^{20}_D$ +6.5 (*c* 0.99, acetone).

^{1}H NMR (acetone-d_6): δ 8.81 (s, 1H), 7.53 (t, $^3J_{HH}$ = 7.8 Hz, 1H), 7.39 (d, $^3J_{HH}$ = 7.5 Hz, 2H), 4.64-4.44 (m, 5H), 4.08-4.04 (m, 1H), 3.99 (ddd, $^2J_{HH}$ = 11.7 Hz and $^3J_{HH}$ = 10.2 and 5.7 Hz, 1H), 3.82 (dd, $^3J_{HH}$ =10.4 and 4.1 Hz, 1H), 3.20-3.11 (m, 2H), 1.31 (d, $^3J_{HH}$ = 6.8 Hz, 3H), 1.30 (d, $^3J_{HH}$ = 6.8 Hz, 3H), 1.23 (d, $^3J_{HH}$ = 6.7 Hz, 3H), 1.22 (d, $^3J_{HH}$ = 6.8 Hz, 3H), 1.14 (s, 9H). ^{13}C NMR (acetone-d_6): δ 161.3, 147.8, 147.7, 131.9, 131.4, 125.69, 125.66, 71.5, 57.8, 54.2, 49.9, 34.3, 29.3, 29.2, 27.5, 25.10, 25.05, 23.99, 23.96. Anal. Calcd for $C_{21}H_{35}F_6N_2OP$: C, 52.94; H, 7.40. Found: C, 52.87; H, 7.31.

(*S*)-9

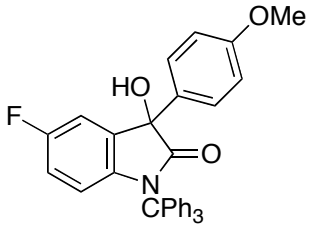


Trimethylsilyldiazomethane (1.0 mL, 0.60 mmol; 10 wt% in hexane) was added dropwise to a solution of compound (*S*)-**8c** (63.1 mg, 0.150 mmol) and HBF_4*aq* (32.0 mg, 0.150 mmol; 42 wt%) in CH_2Cl_2 (1.0 mL) at 0 °C. The reaction mixture was stirred for 10 min at 0 °C and it was poured into H_2O. After extraction with CH_2Cl_2, the organic layer was dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was chromatographed on silica gel with acetone/CH_2Cl_2 = 1/5 to afford compound (*S*)-**9** as a white solid (54.9 mg, 0.126 mmol; 84% yield). $[\alpha]^{20}_D$ –2.1 (*c* 0.50, acetone).

^{1}H NMR (acetone-d_6): δ 8.72 (s, 1H), 7.34 (t, $^3J_{HH}$ = 7.6 Hz, 1H), 7.26 (d, $^3J_{HH}$ = 8.1 Hz, 2H), 4.58-4.46 (m, 4H), 3.93 (dd, $^2J_{HH}$ = 9.6 Hz and $^3J_{HH}$ = 2.5 Hz, 1H), 3.90 (dd, $^2J_{HH}$ = 9.8 Hz and $^3J_{HH}$ = 8.9 Hz, 1H), 3.85 (dd, $^3J_{HH}$ = 8.9 and 2.4 Hz, 1H), 3.45 (s, 3H), 2.38 (s, 6H), 1.16 (s, 9H). ^{13}C NMR (acetone-d_6): δ 161.1, 136.9, 134.5, 131.1, 130.0, 68.9, 68.4, 59.0, 51.5, 50.4, 34.4, 27.5, 17.6. HRMS (ESI-TOF) calcd for $C_{18}H_{29}N_2O$ ($M–PF_6^-$) 289.2274, found 289.2275.

III. Catalytic and Stoichiometric Reactions

Procedure for Equation 1.

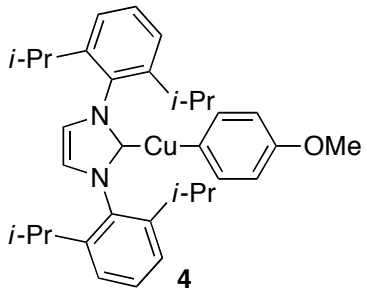


3aa

A solution of CuO*t*-Bu(IPr) (10.5 mg, 20.0 μmol), isatin **1a** (81.5 mg, 0.200 mmol), 4-methoxyphenylboronate **2a** (52.8 mg, 0.240 mmol), and KO*t*-Bu (22.4 mg, 0.200 mmol) in dioxane (1.0 mL) was stirred for 15 h at 30 °C. The reaction was quenched with H_2O (60 μL), and this was passed through a pad of silica gel with EtOAc. The solvent was removed under vacuum, and the residue was purified by silica gel preparative TLC with EtOAc/hexane = 1/2 to afford product **3aa** as a white solid (84.7 mg, 0.164 mmol; 82% yield).

^{1}H NMR ($CDCl_3$): δ 7.39-7.34 (m, 8H), 7.25-7.18 (m, 9H), 7.01 (dd, $^3J_{HF}$ = 7.4 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.92 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 6.64 (td, ^3J = 9.0 Hz and $^4J_{HH}$ = 2.7 Hz, 1H), 6.28 (dd, $^3J_{HH}$ = 8.9 Hz and $^4J_{HF}$ = 4.0 Hz, 1H), 3.83 (s, 3H), 3.13 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.5, 159.9, 159.1 (d, $^1J_{CF}$ = 243 Hz), 141.7, 139.0 (d, $^4J_{CF}$ = 2.1 Hz), 133.6 (d, $^3J_{CF}$ = 7.2 Hz), 132.2, 129.2, 127.9, 127.2, 127.0, 117.1 (d, $^3J_{CF}$ = 7.2 Hz), 114.8 (d, $^2J_{CF}$ = 22.7 Hz), 114.3, 112.2 (d, $^2J_{CF}$ = 24.8 Hz), 77.4, 74.7, 55.4. Anal. Calcd for $C_{34}H_{26}FNO_3$: C, 79.21; H, 5.08. Found: C, 78.91; H, 4.95.

Procedure for Equation 2.[5]

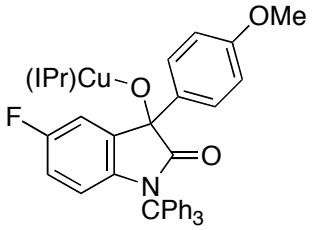


4

4-Methoxyphenylboronate **2a** (220 mg, 1.00 mmol) was added to a solution of CuO*t*-Bu(IPr) (525 mg, 1.00 mmol) in dioxane (10 mL) at room temperature. The reaction mixture was stirred for 30 min at 30 °C, and then the solvent was removed under vacuum. The residue was washed with hexane to afford compound **4** (CAS 1064085-74-0) as a pale yellow solid (489 mg, 0.874 mmol; 87% yield).

^{1}H NMR (C_6D_6): δ 7.54 (d, $^3J_{HH}$ = 8.3 Hz, 2H), 7.24 (t, $^3J_{HH}$ = 7.8 Hz, 2H), 7.10 (d, $^3J_{HH}$ = 7.8 Hz, 4H), 6.90 (d, $^3J_{HH}$ = 8.3 Hz, 2H), 6.31 (s, 2H), 3.39 (s, 3H), 2.66 (sept, $^3J_{HH}$ = 6.8 Hz, 4H), 1.43 (d, $^3J_{HH}$ = 6.8 Hz, 12H), 1.11 (d, $^3J_{HH}$ = 6.8 Hz, 12H). ^{13}C NMR (C_6D_6): δ 186.1, 158.0, 155.8, 145.9, 141.1, 135.4, 130.5, 124.2, 122.3, 112.6, 54.4, 29.1, 25.2, 23.7.

Procedure for Equation 3.



5

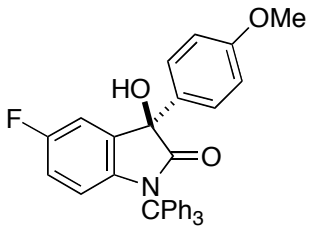
A solution of isatin **1a** (112 mg, 0.200 mmmol) and compound **4** (81.5 mg, 0.200 mmol) in dioxane (2.0 mL) was stirred for 30 min at 30 °C. The solvent was removed under vacuum to afford compound **5** as a pale yellow solid (203 mg, 0.199 mmol; 99% yield). The structure was confirmed by X-ray crystallographic analysis after recrystallization from *n*-Bu_2O/pentane at room temperature.

^{1}H NMR (C_6D_6): δ 7.50-7.46 (m, 8H), 7.30 (t, $^3J_{HH}$ = 7.8 Hz, 2H), 7.12 (d, $^3J_{HH}$ = 8.0 Hz, 2H), 7.10 (d, $^3J_{HH}$ = 8.2 Hz, 2H), 7.03-7.00 (m, 1H), 7.00 (t, $^3J_{HH}$ = 7.6 Hz, 6H), 6.94 (t, $^3J_{HH}$ = 7.3 Hz, 3H), 6.67 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 6.30-6.23 (m, 2H), 6.27 (s, 2H), 3.44 (s, 3H), 2.64-2.56 (m, 4H), 1.31 (d, $^3J_{HH}$ = 6.8 Hz, 6H), 1.21 (d, $^3J_{HH}$ = 6.9 Hz, 6H), 1.09 (d, $^3J_{HH}$ = 6.9 Hz, 6H), 1.05 (d, $^3J_{HH}$ = 6.8 Hz, 6H). ^{13}C NMR (C_6D_6): δ 186.2, 183.6, 159.3 (d, $^1J_{CF}$ = 241 Hz), 158.6, 145.9, 143.7, 142.9, 141.6, 138.8, 135.5, 130.5, 129.8, 127.8, 127.6, 126.4, 124.3 (d, $^3J_{CF}$ = 7.2 Hz), 122.5, 115.8 (d, $^3J_{CF}$ = 6.2 Hz), 113.5, 112.3 (d, $^2J_{CF}$ = 23.8 Hz), 111.8 (d, $^2J_{CF}$ = 23.8 Hz), 83.0, 74.2, 54.8, 29.0, 24.9, 24.7, 24.1, 24.0. HRMS (ESI-TOF) calcd for $C_{61}H_{62}CuFN_3O_3$ ($M+H^+$) 966.4066, found 966.4091.

[5] T. Ohnishi, M. Nishiura and Z. Hou, *Angew. Chem., Int. Ed.* 2008, **47**, 5792.

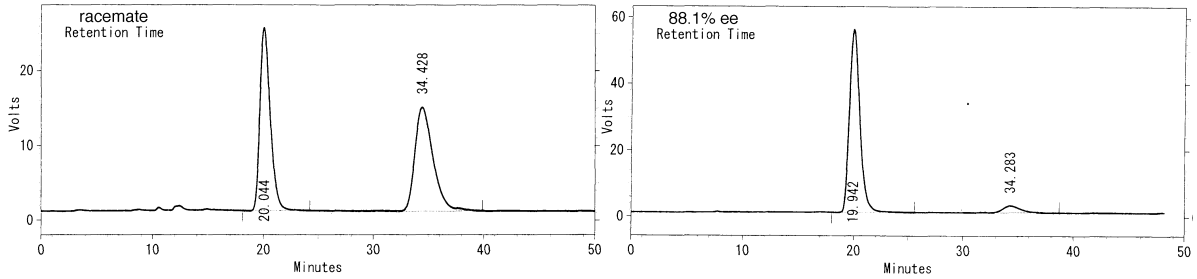
General Procedure for Table 2.

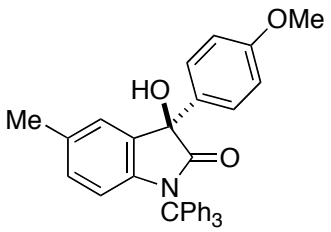
A solution of CuCl (3.0 mg, 30 μmol), (*S*)-**8c** (13.9 mg, 33 μmol), and KO*t*-Bu (40.4 mg, 0.36 mmol) in THF (0.75 mL) was stirred for 15 min at room temperature. The solvent was removed under vacuum and the residue was dissolved in dioxane (0.75 mL). Arylboronate **2** (0.36 mmol) was added to it and the mixture was stirred for 5 min at room temperature. Isatin **1** (0.30 mmol) was then added to this mixture with additional dioxane (0.75 mL), and the resulting mixture was stirred for 15 h at 30 °C. The reaction was quenched with H_2O (90 μL) and this was passed through a pad of silica gel with EtOAc. The solvent was removed under vacuum, and the residue was purified by silica gel preparative TLC with EtOAc/hexane to afford product **3**.



3aa

Entry 1. White solid. 80% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 19.9 min [major enantiomer], 34.3 min [minor enantiomer]. 88% ee. $[\alpha]^{20}_{D}$ –5.0 (*c* 0.98, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

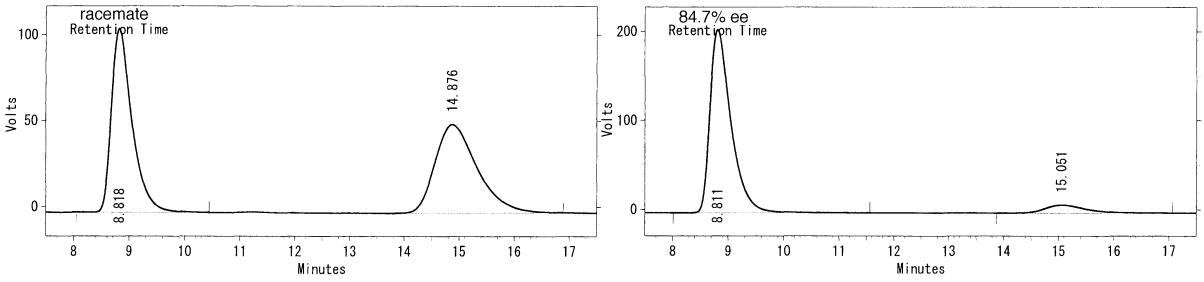


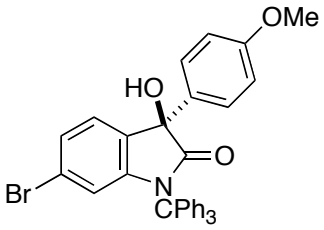


3ba

Entry 2. Pale yellow solid. 67% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.8 mL/min. Retention times: 8.8 min [major enantiomer], 15.1 min [minor enantiomer]. 85% ee. $[\alpha]^{20}_{D}$ –42.6 (*c* 0.50, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.39 (d, $^3J_{HH}$ = 7.2 Hz, 6H), 7.36 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 7.22 (t, $^3J_{HH}$ = 7.3 Hz, 6H), 7.17 (t, $^3J_{HH}$ = 7.1 Hz, 3H), 7.09 (d, $^4J_{HH}$ = 1.3 Hz, 1H), 6.90 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 6.74 (dd, $^3J_{HH}$ = 8.4 Hz and $^4J_{HH}$ = 1.3 Hz, 1H), 6.22 (d, $^3J_{HH}$ = 8.3 Hz, 1H), 3.81 (s, 3H), 3.13 (s, 1H), 2.20 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 179.7, 159.7, 142.0, 140.9, 132.9, 132.7, 131.9, 129.3, 128.8, 127.9, 127.1, 127.0, 125.1, 116.1, 114.2, 77.4, 74.5, 55.5, 20.9. Anal. Calcd for $C_{35}H_{29}NO_3$: C, 82.17; H, 5.71. Found: C, 82.03; H, 5.86.

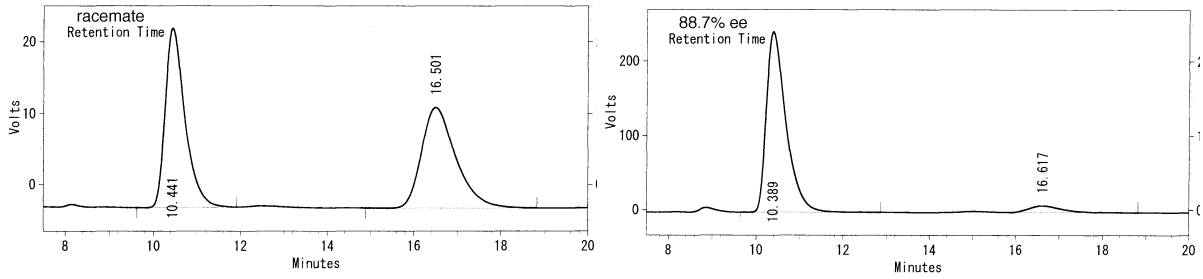


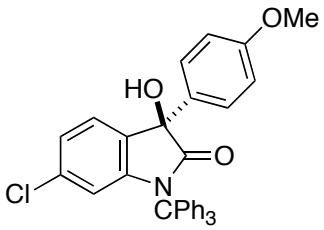


3ca

Entry 3. Pale yellow solid. 83% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.8 mL/min. Retention times: 10.4 min [major enantiomer], 16.6 min [minor enantiomer]. 89% ee. $[\alpha]^{20}_{D}$ –50.2 (*c* 1.00, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.36 (d, $^3J_{HH}$ = 7.2 Hz, 6H), 7.32 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 7.26-7.20 (m, 9H), 7.14 (d, $^3J_{HH}$ = 7.9 Hz, 1H), 7.11 (d, $^3J_{HH}$ = 7.9 Hz, 1H), 6.90 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 6.42 (s, 1H), 3.82 (s, 3H), 3.10 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.3, 159.8, 144.5, 141.5, 132.0, 130.9, 129.1, 128.0, 127.2, 127.0, 125.9, 125.7, 121.9, 119.2, 114.2, 76.9, 74.7, 55.4. Anal. Calcd for $C_{34}H_{26}BrNO_3$: C, 70.84; H, 4.55. Found: C, 70.68; H, 4.54.

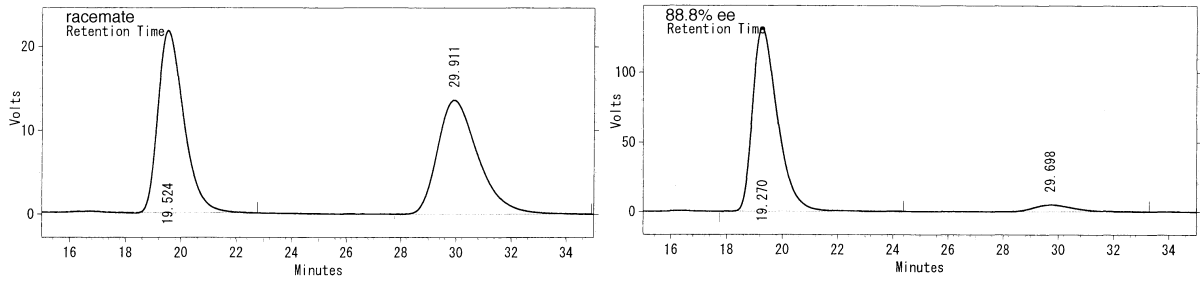


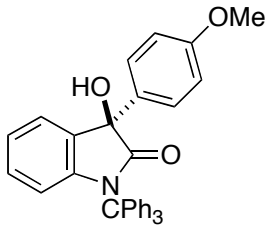


3da

Entry 4. Pale yellow solid. 70% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 19.3 min [major enantiomer], 29.7 min [minor enantiomer]. 89% ee. $[\alpha]^{20}_{D}$ –40.5 (*c* 0.99, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.36 (d, $^3J_{HH}$ = 7.1 Hz, 6H), 7.32 (d, $^3J_{HH}$ = 8.9 Hz, 2H), 7.27-7.18 (m, 10H), 6.96 (dd, $^3J_{HH}$ = 8.1 Hz and $^4J_{HH}$ = 1.8 Hz, 1H), 6.90 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 6.28 (d, $^4J_{HH}$ = 1.7 Hz, 1H), 3.82 (s, 3H), 3.11 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.4, 159.8, 144.4, 141.5, 133.9, 132.1, 130.3, 129.1, 128.0, 127.2, 127.0, 125.4, 123.0, 116.5, 114.2, 76.9, 74.7, 55.4. Anal. Calcd for $C_{34}H_{26}ClNO_3$: C, 76.76; H, 4.93. Found: C, 76.50; H, 4.90.

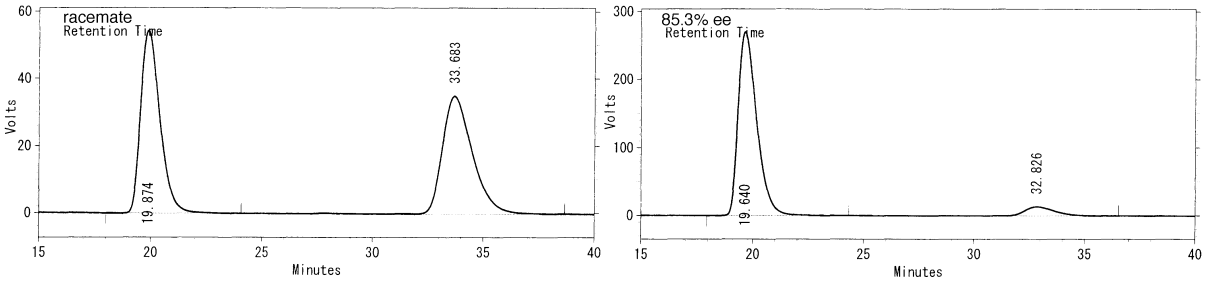


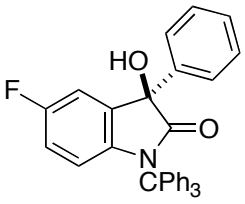


3ea

Entry 5. The reaction was conducted for 36 h. Pale yellow solid. 76% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 19.6 min [major enantiomer], 32.8 min [minor enantiomer]. 85% ee. $[\alpha]^{20}_{D}$ –18.4 (*c* 1.01, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.39 (d, $^3J_{HH}$ = 7.1 Hz, 6H), 7.36 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 7.28 (dd, $^3J_{HH}$ = 6.7 Hz and $^4J_{HH}$ = 1.7 Hz, 1H), 7.23 (t, $^3J_{HH}$ = 7.3 Hz, 6H), 7.19 (t, $^3J_{HH}$ = 7.1 Hz, 3H), 6.99-6.93 (m, 2H), 6.91 (d, $^3J_{HH}$ = 8.8 Hz, 2H), 6.35 (dd, $^3J_{HH}$ = 7.5 Hz and $^4J_{HH}$ = 1.2 Hz, 1H), 3.82 (s, 3H), 3.10 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.7, 159.8, 143.3, 142.0, 132.7, 131.9, 129.3, 128.3, 127.9, 127.11, 127.06, 124.5, 123.0, 116.2, 114.2, 77.3, 74.5, 55.4. Anal. Calcd for $C_{34}H_{27}NO_3$: C, 82.07; H, 5.47. Found: C, 81.80; H, 5.41.



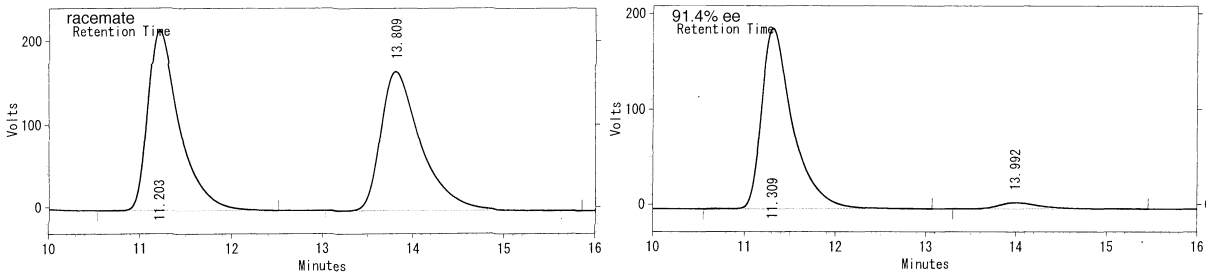


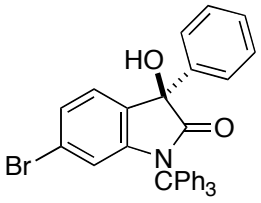
3ab

Entry 6. White solid. 74% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 11.3 min [major enantiomer], 14.0 min [minor enantiomer]. 91% ee. $[\alpha]^{20}_{D}$ +4.0 (*c* 0.98, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.44-7.34 (m, 11H), 7.26-7.19 (m, 9H), 6.98 (dd, $^3J_{HF}$ = 7.4 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.65 (td, ^3J = 8.9 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.30 (dd, $^3J_{HH}$ = 9.0 Hz and $^4J_{HF}$ = 4.1 Hz, 1H), 3.21 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.3, 159.1 (d, $^1J_{CF}$ = 244 Hz), 141.7,

140.2, 139.1 (d, $^4J_{CF}$ = 3.1 Hz), 133.6 (d, $^3J_{CF}$ = 8.3 Hz), 129.2, 128.9, 128.6, 127.9, 127.2, 125.4, 117.2 (d, $^3J_{CF}$ = 7.2 Hz), 114.9 (d, $^2J_{CF}$ = 22.7 Hz), 112.3 (d, $^2J_{CF}$ = 23.8 Hz), 77.8 (d, $^4J_{CF}$ = 2.1 Hz), 74.8. Anal. Calcd for $C_{33}H_{24}FNO_2$: C, 81.63; H, 4.98. Found: C, 81.73; H, 5.01.

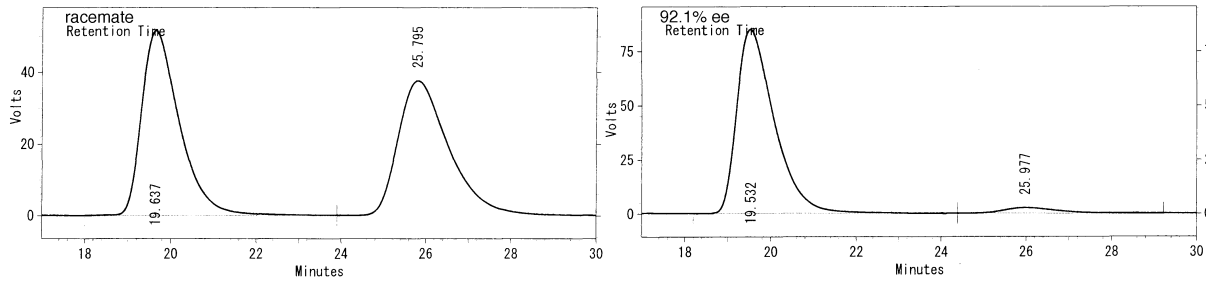


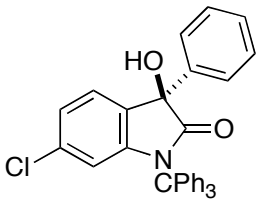


3cb

Entry 7. White solid. 83% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 95/5, flow = 0.5 mL/min. Retention times: 19.5 min [major enantiomer], 26.0 min [minor enantiomer]. 92% ee. $[\alpha]^{20}_D$ –19.3 (*c* 0.50, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.41-7.34 (m, 11H), 7.28-7.21 (m, 9H), 7.119 (s, 1H), 7.117 (s, 1H), 6.44 (s, 1H), 3.14 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.2, 144.7, 141.5, 140.1, 130.8, 129.2, 128.9, 128.7, 128.0, 127.4, 126.1, 125.8, 125.5, 122.1, 119.4, 77.4, 74.9. Anal. Calcd for $C_{33}H_{24}BrNO_2$: C, 72.53; H, 4.43. Found: C, 72.41; H, 4.37.



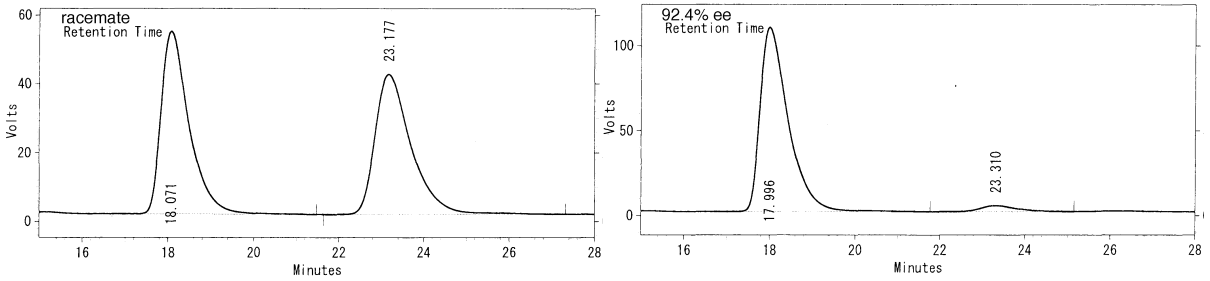


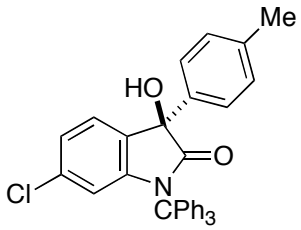
3db

Entry 8. Pale yellow solid. 87% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 95/5, flow = 0.5 mL/min. Retention times: 18.0 min [major enantiomer], 23.3 min [minor enantiomer]. 92% ee. $[\alpha]^{20}_D$ –32.5 (*c* 0.50, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.41-7.34 (m, 11H), 7.28-7.20 (m, 9H), 7.18 (d, $^3J_{HH}$ = 7.9 Hz, 1H), 6.96 (dd, $^3J_{HH}$ = 7.9 Hz and $^4J_{HH}$ = 1.8 Hz, 1H), 6.30 (d, $^4J_{HH}$ = 1.7 Hz, 1H), 3.15 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.3, 144.6, 141.5, 140.2, 134.2, 130.3, 129.2, 128.9, 128.7, 128.0, 127.3,

125.5, 125.4, 123.2, 116.6, 77.3, 74.9. Anal. Calcd for $C_{33}H_{24}ClNO_2$: C, 78.95; H, 4.82. Found: C, 78,74; H, 4.75.

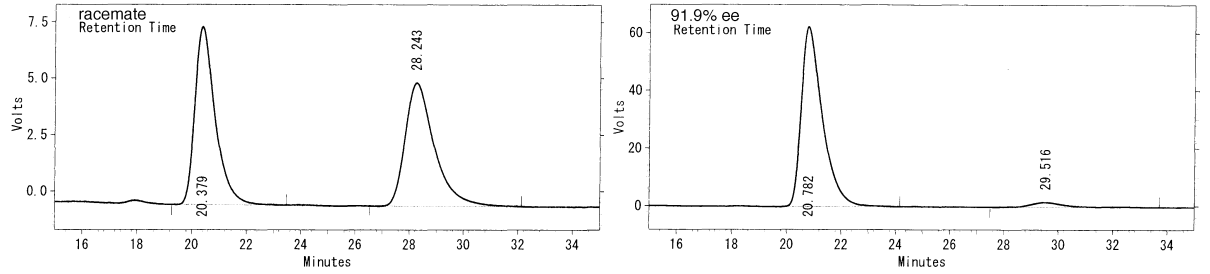


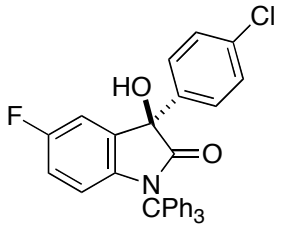


3dc

Entry 9. White solid. 87% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 95/5, flow = 0.5 mL/min. Retention times: 20.8 min [major enantiomer], 29.5 min [minor enantiomer]. 92% ee. $[\alpha]^{20}_{D}$ –35.1 (*c* 0.50, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.38-7.35 (m, 6H), 7.29-7.16 (m, 14H), 6.95 (dd, $^3J_{HH}$ = 7.9 Hz and $^3J_{HH}$ = 1.8 Hz, 1H), 6.29 (d, $^4J_{HH}$ = 1.7 Hz, 1H), 3.10 (s, 1H), 2.36 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 179.4, 144.5, 141.5, 138.5, 137.2, 134.0, 130.4, 129.6, 129.2, 128.0, 127.3, 125.5, 125.4, 123.1, 116.6, 77.2, 74.8, 21.3. Anal. Calcd for $C_{34}H_{26}ClNO_2$: C, 79.14; H, 5.08. Found: C, 79.14; H, 5.16.



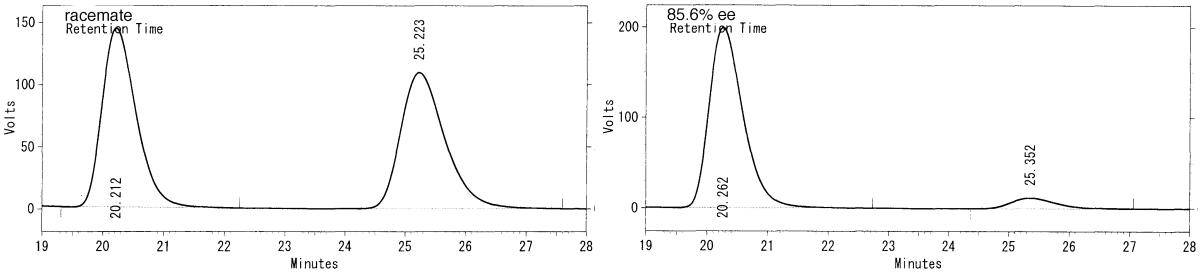


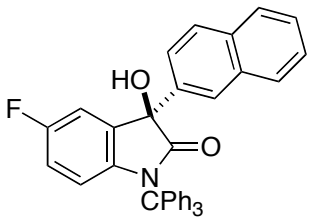
3ad

Entry 10. Pale yellow solid. 78% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 20.3 min [major enantiomer], 25.4 min [minor enantiomer]. 86% ee. $[\alpha]^{20}_{D}$ +12.2 (*c* 0.99, $CHCl_3$). The absolute configuration was determined by X-ray crystallographic analysis after recrystallization from Et_2O in the presence of DMF in a freezer (ee of the crystals: 99% ee).

^{1}H NMR ($CDCl_3$): δ 7.38-7.30 (m, 10H), 7.26-7.19 (m, 9H), 6.95 (dd, $^3J_{HF}$ = 7.3 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.66 (td, ^3J = 8.9 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.31 (dd, $^3J_{HH}$ = 9.0 Hz and

$^4J_{HF}$ = 4.1 Hz, 1H), 3.23 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 178.9, 159.1 (d, $^1J_{CF}$ = 243 Hz), 141.6, 139.0 (d, $^4J_{CF}$ = 2.1 Hz), 138.8, 134.6, 133.3 (d, $^3J_{CF}$ = 7.2 Hz), 129.2, 129.0, 128.0, 127.3, 127.0, 117.4 (d, $^3J_{CF}$ = 7.2 Hz), 115.1 (d, $^2J_{CF}$ = 22.7 Hz), 112.2 (d, $^2J_{CF}$ = 23.8 Hz), 77.4, 75.0. Anal. Calcd for $C_{33}H_{23}ClFNO_2$: C, 76.22; H, 4.46. Found: C, 76.23; H, 4.74.

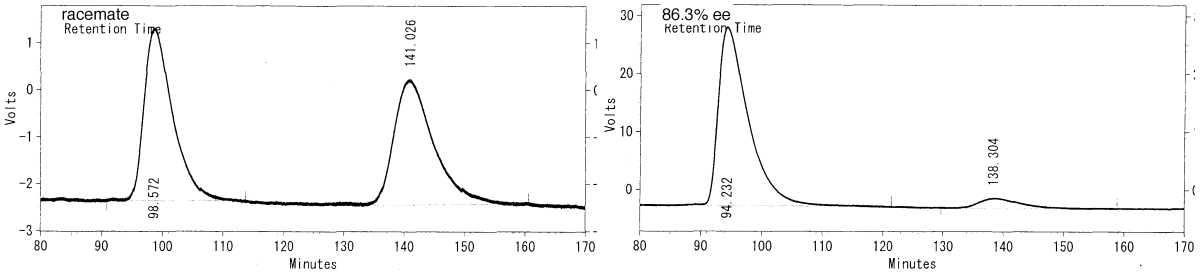


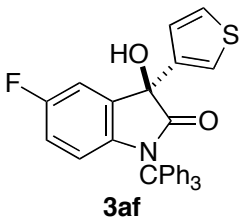


3ae

Entry 11. White solid. 85% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 100/1, flow = 1.0 mL/min. Retention times: 94.2 min [major enantiomer], 138.3 min [minor enantiomer]. 86% ee. $[\alpha]^{20}_D$ +52.8 (*c* 1.01, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.91 (s, 1H), 7.87-7.83 (m, 3H), 7.53-7.50 (m, 2H), 7.46 (dd, $^3J_{HH}$ = 8.7 Hz and $^4J_{HH}$ = 1.9 Hz, 1H), 7.42 (d, $^3J_{HH}$ = 7.0 Hz, 6H), 7.27-7.19 (m, 9H), 7.02 (dd, $^3J_{HF}$ = 7.3 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.68 (td, ^3J = 9.0 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.34 (dd, $^3J_{HH}$ = 9.0 Hz and $^4J_{HF}$ = 4.1 Hz, 1H), 3.32 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 179.2, 159.1 (d, $^1J_{CF}$ = 242 Hz), 141.7, 139.1 (d, $^4J_{HF}$ = 3.1 Hz), 137.5, 133.6 (d, $^3J_{CF}$ = 7.2 Hz), 133.24, 133.21, 129.2, 128.8, 128.5, 127.9, 127.7, 127.2, 126.6, 126.5, 124.7, 123.1, 117.2 (d, $^3J_{CF}$ = 8.2 Hz), 115.0 (d, $^2J_{CF}$ = 22.6 Hz), 112.4 (d, $^2J_{CF}$ = 24.6 Hz), 78.0, 74.9. Anal. Calcd for $C_{37}H_{26}FNO_2$: C, 82.97; H, 4.89. Found: C, 82.80; H, 5.05.



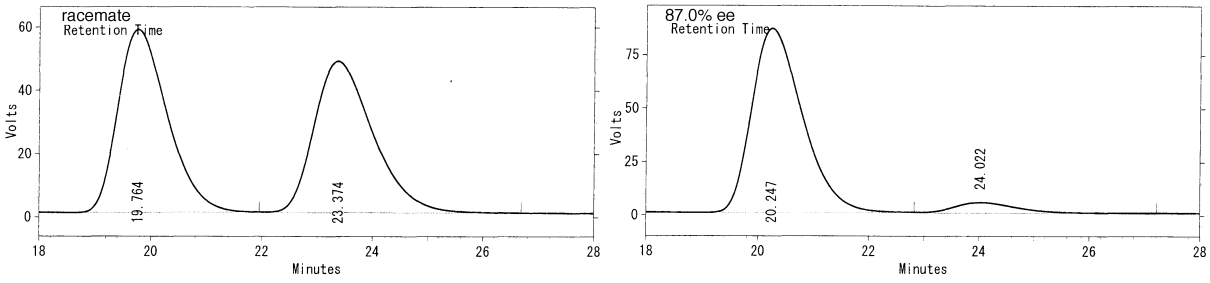


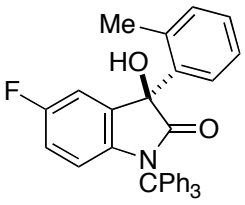
3af

Entry 12. White solid. 94% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 20.2 min [major enantiomer], 24.0 min [minor enantiomer]. 87% ee. $[\alpha]^{20}_D$ –9.1 (*c* 0.50, $CHCl_3$). The

absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.39-7.36 (m, 7H), 7.30 (dd, $^4J_{HH}$ = 2.8 and 0.9 Hz, 1H), 7.27-7.19 (m, 9H), 7.14 (dd, $^3J_{HH}$ = 5.0 Hz and $^4J_{HH}$ = 0.8 Hz, 1H), 7.11 (dd, $^3J_{HF}$ = 7.4 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.65 (td, ^3J = 9.0 Hz and $^4J_{HH}$ = 2.9 Hz, 1H), 6.27 (dd, $^3J_{HH}$ = 8.9 Hz and $^4J_{HF}$ = 4.1 Hz, 1H), 3.21 (s, 1H). ^{13}C NMR ($CDCl_3$): δ 178.8, 159.1 (d, $^1J_{CF}$ = 242 Hz), 141.6, 141.2, 138.8, 132.8 (d, $^3J_{CF}$ = 7.2 Hz), 129.3, 128.0, 127.3, 127.2, 125.5, 123.1, 117.2 (d, $^3J_{CF}$ = 8.2 Hz), 115.0 (d, $^2J_{CF}$ = 22.6 Hz), 112.0 (d, $^2J_{CF}$ = 24.7 Hz), 75.8, 74.7. Anal. Calcd for $C_{31}H_{22}FNO_2S$: C, 75.74; H, 4.51. Found: C, 75.50; H, 4.39.

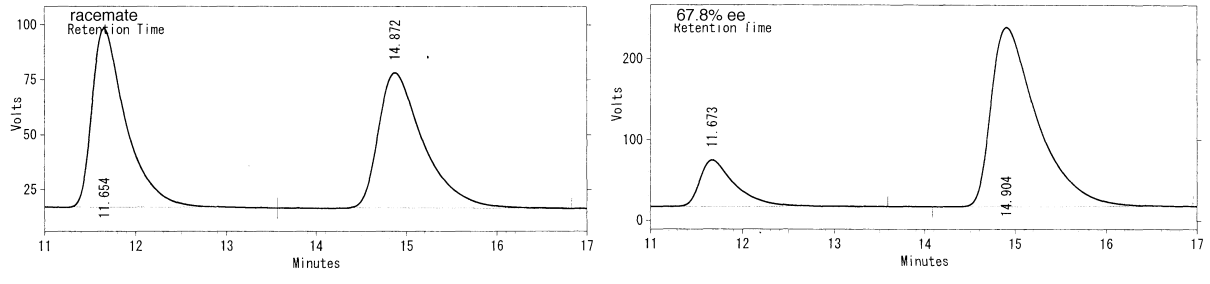


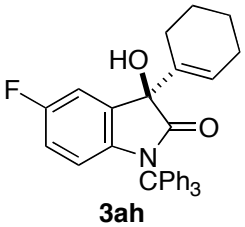


3ag

Entry 13. White solid. 74% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 95/5, flow = 0.5 mL/min. Retention times: 11.7 min [minor enantiomer], 14.9 min [major enantiomer]. 68% ee. $[\alpha]^{20}_D$ +112 (*c* 1.00, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.81 (d, $^3J_{HH}$ = 7.7 Hz, 1H), 7.52 (d, $^3J_{HH}$ = 7.9 Hz, 6H), 7.27 (t, $^3J_{HH}$ = 7.8 Hz, 6H), 7.24-7.17 (m, 5H), 6.96 (d, $^3J_{HF}$ = 7.4 Hz, 1H), 6.70-6.64 (m, 2H), 6.25 (dd, $^3J_{HH}$ = 8.7 Hz and $^4J_{HF}$ = 4.1 Hz, 1H), 3.29 (s, 1H), 1.34 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 177.4, 158.9 (d, $^1J_{CF}$ = 244 Hz), 141.7, 139.9 (d, $^4J_{CF}$ = 2.1 Hz), 137.2, 135.1, 132.8 (d, $^3J_{CF}$ = 8.3 Hz), 131.5, 129.2, 128.5, 127.9, 127.1, 126.2, 125.9, 116.6 (d, $^3J_{CF}$ = 7.2 Hz), 115.0 (d, $^2J_{CF}$ = 23.8 Hz), 112.5 (d, $^2J_{CF}$ = 23.8 Hz), 77.7, 74.5, 19.5. HRMS (ESI-TOF) calcd for $C_{34}H_{36}FNO_2Na$ (M+Na$^+$) 522.1840, found 522.1828.

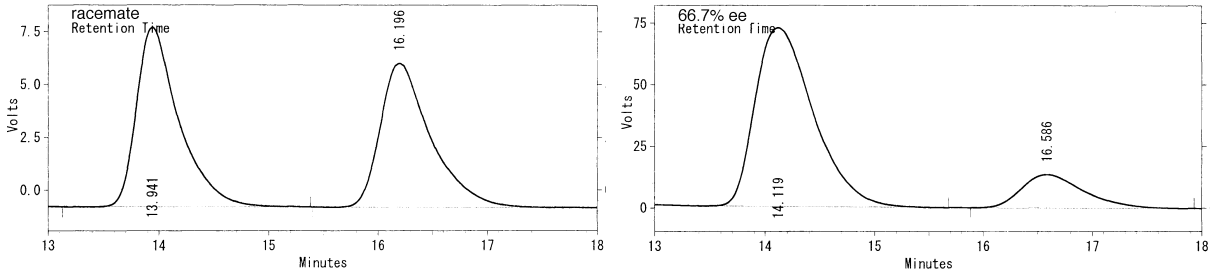




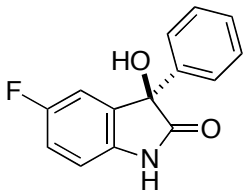
3ah

Entry 14. White solid. 72% yield. The ee was determined on a Daicel Chiralcel OD-H column with hexane/2-propanol = 95/5, flow = 0.7 mL/min. Retention times: 14.1 min [major enantiomer], 16.6 min [minor enantiomer]. 67% ee. $[\alpha]^{20}_{D}$ +16.9 (*c* 0.36, $CHCl_3$). The absolute configuration was assigned by analogy with entry 10.

^{1}H NMR ($CDCl_3$): δ 7.40 (d, $^3J_{HH}$ = 7.2 Hz, 6H), 7.26 (t, $^3J_{HH}$ = 7.4 Hz, 6H), 7.21 (tt, $^3J_{HH}$ = 7.1 Hz and $^4J_{HH}$ = 1.3 Hz, 3H), 6.96 (dd, $^3J_{HF}$ = 7.4 Hz and $^4J_{HH}$ = 2.8 Hz, 1H), 6.60 (td, ^3J = 9.0 Hz and $^4J_{HH}$ = 2.9 Hz, 1H), 6.22 (dd, $^3J_{HH}$ = 8.9 Hz and $^4J_{HF}$ = 4.2 Hz, 1H), 6.03-6.00 (m, 1H), 2.71 (s, 1H), 2.15-2.10 (m, 2H), 2.01-1.93 (m, 1H), 1.88-1.82 (m, 1H), 1.72-1.65 (m, 1H), 1.64-1.54 (m, 3H). ^{13}C NMR ($CDCl_3$): δ 179.2, 159.0 (d, $^1J_{CF}$ = 243 Hz), 141.8, 139.5, 136.3, 132.3 (d, $^3J_{CF}$ = 7.2 Hz), 129.3, 127.9, 127.2, 124.3, 116.9 (d, $^3J_{CF}$ = 8.3 Hz), 114.5 (d, $^2J_{CF}$ = 23.8 Hz), 111.7 (d, $^2J_{CF}$ = 23.8 Hz), 78.9, 74.7, 25.3, 23.7, 22.6, 22.1. Anal. Calcd for $C_{31}H_{22}FNO_2S$: C, 75.74; H, 4.51. Found: C, 75.50; H, 4.39. HRMS (ESI-TOF) calcd for $C_{33}H_{28}FNO_2Na$ ($M+Na^+$) 512.1996, found 512.1997.



Procedure for Equation 5.[6]



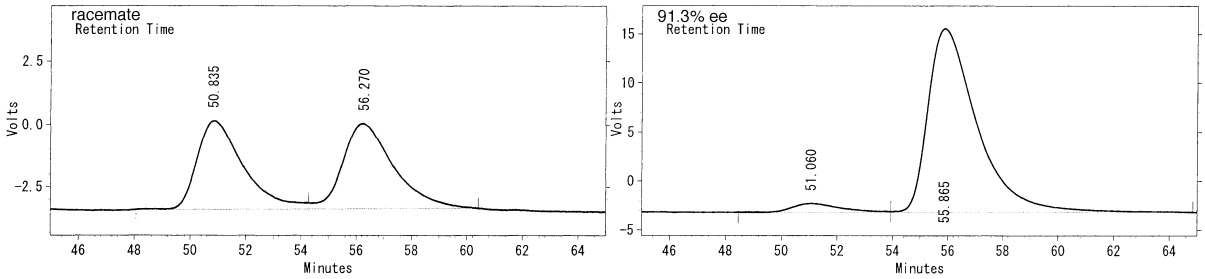
10

Triethylsilane (32.0 μL, 0.200 mmol) and trifluoroacetic acid (0.60 mL) were added to a solution of **3ab** (23.1 mg, 47.6 μmol; 91% ee) in CH_2Cl_2 (2.0 mL), and the mixture was stirred for 2 h at room temperature. The reaction was quenched with saturated $NaHCO_3$*aq* and extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$, filtered, and concentrated under vacuum. The residue was purified by silica gel preparative TLC with EtOAc/hexane = 1/3 to afford compound **10** (CAS 1190310-35-0) as a white solid (10.9 mg, 44.8 μmol, 94% yield).

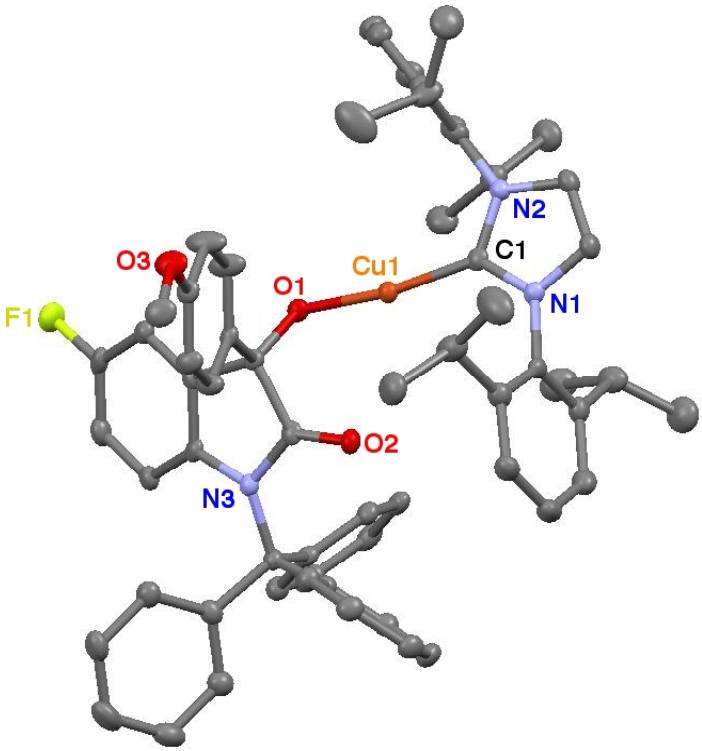
The ee was determined on two Daicel Chiralcel OD-H columns with hexane/2-propanol = 90/10, flow = 0.5 mL/min. Retention times: 51.1 min [minor enantiomer], 55.9 min [major enantiomer]. 91% ee. $[\alpha]^{20}_{D}$ +4.5 (*c* 0.50, MeOH).

^{1}H NMR (DMSO-d_6): δ 10.42 (s, 1H), 7.34-7.26 (m, 5H), 7.09 (ddd, $^3J_{HF}$ = 9.5 Hz, $^3J_{HH}$ = 8.7 Hz, and $^4J_{HH}$ = 2.7 Hz, 1H), 6.96 (dd, $^3J_{HF}$ = 8.0 Hz and $^4J_{HH}$ = 2.6 Hz, 1H), 6.90 (dd, $^3J_{HH}$ = 8.4 Hz and $^4J_{HF}$ = 4.3 Hz, 1H), 6.75 (s, 1H). ^{13}C NMR (DMSO-d_6): δ 178.4, 158.2 (d, $^1J_{CF}$ = 238 Hz), 141.0, 138.1 (d, $^4J_{CF}$ = 2.1 Hz), 135.4 (d, $^3J_{CF}$ = 7.2 Hz), 128.2, 127.6, 125.4, 115.5 (d, $^2J_{CF}$ = 23.8 Hz), 112.3 (d, $^2J_{CF}$ = 24.8 Hz), 110.8 (d, $^3J_{CF}$ = 8.3 Hz), 77.6.

[6] A. Volonterio and M. Zanda, *J. Org. Chem.* 2008, **73**, 7486.


racemate
Retention Time
50.835
56.270
Volts
Minutes
91.3% ee
Retention Time
51.060
55.865
Volts
Minutes

IV. X-ray Crystal Structure of Compound 5



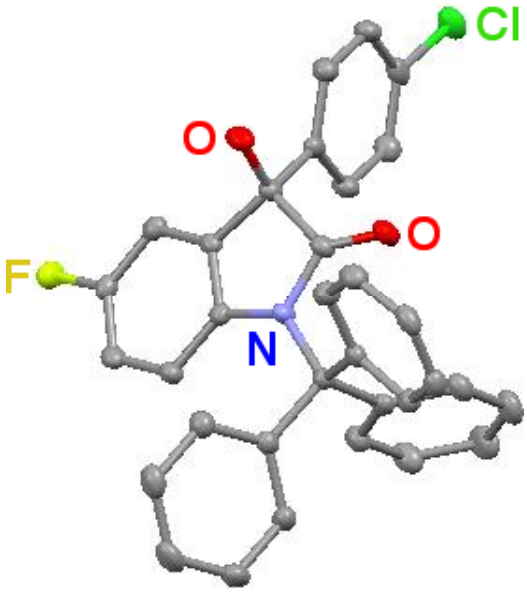
The crystal structure has been deposited at the Cambridge Crystallographic Data Centre (deposition number: CCDC 775074). The data can be obtained free of charge via the Internet at www.ccdc.cam.ac.uk/conts/retrieving.html.

Crystal Data and Structure Refinement.

Empirical Formula	$C_{66}H_{73}CuFN_3O_3$
Formula Weight	1038.81
Temperature	90 ± 2 K
Wavelength	0.71069 Å
Crystal System	Monoclinic
Space Group	$P2_1/c$
Unit Cell Dimensions	a = 13.033(2) Å b = 10.3280(18) Å c = 42.357(7) Å β = 90.232(3)°
Volume	5701.4(17) $Å^3$
Z Value	4

Calculated Density	1.210 g/cm^3
Absorption Coefficient	0.434 mm^{-1}
F(000)	2208
Crystal Size	0.50 x 0.20 x 0.10 mm
Theta Range for Data Collection	0.96–27.00°
Index Ranges	$-16 \le h \le 16, -11 \le k \le 13, -45 \le l \le 53$
Reflections Collected	32893
Independent Reflections	12311 [R(int) = 0.0304]
Completeness to Theta = 27.00	98.9%
Max. and Min. Transmission	0.9578 and 0.8121
Refinement Method	Full-matrix least-squares on F^2
Data / Restraints / Parameters	12311 / 0 / 667
Goodness-of-Fit on F^2	1.166
Final R Indices [I>2sigma(I)]	R1 = 0.0669, wR2 = 0.1500
R Indices (All Data)	R1 = 0.0771, wR2 = 0.1543
Largest Diff. Peak and Hole	1.192 and –0.856 $e^-/Å^3$

V. X-ray Crystal Structure of Compound 3ad



Data Collection

A colorless Et_2O solution of compound **4** containing a small amount of DMF was prepared. Crystals suitable for X-ray analysis were obtained by cooling the solution in a freezer (–20 °C).

A colorless prism crystal of $C_{36}H_{30}O_3N_2ClF$ having approximate dimensions of 0.40 x 0.30 x 0.30 mm was mounted on a glass fiber. All measurements were made on a Rigaku RAXIS RAPID imaging plate area detector with graphite monochromated Mo-Kα radiation.

Indexing was performed from 3 oscillations that were exposed for 30 seconds. The crystal-to-detector distance was 127.40 mm.

Cell constants and an orientation matrix for data collection corresponded to a primitive tetragonal cell (laue class: 4/m) with dimensions:

a = 9.339(2) Å
c = 34.336(6) Å
V = 2994.8(10) $Å^3$

For Z = 4 and F.W. = 593.10, the calculated density is 1.315 g/cm^3. Based on the systematic absences of:

00l: l ± 4n

and the successful solution and refinement of the structure, the space group was determined to be:

$P4_3$ (#78)

The data were collected at a temperature of –150 ± 1 °C to a maximum 2θ value of 55.0°. A total of 44 oscillation images were collected. A sweep of data was done using ω scans from 130.0 to 190.0° in 5.0° step, at χ = 45.0° and ϕ = 30.0°. The exposure rate was 80.0 [sec./°]. A second sweep was performed using ω scans from 0.0 to 160.0° in 5.0° step, at χ = 45.0°

and ϕ = 180.0°. The exposure rate was 80.0 [sec./°]. The crystal-to-detector distance was 127.40 mm. Readout was performed in the 0.100 mm pixel mode.

Data Reduction

Of the 29293 reflections that were collected, 6852 were unique (R_{int} = 0.050).

The linear absorption coefficient, μ, for Mo-Kα radiation is 1.733 cm^{-1}. The data were corrected for Lorentz and polarization effects.

Structure Solution and Refinement

The structure was solved by direct methods[7] and expanded using Fourier techniques.[8] The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined using the riding model. The final cycle of full-matrix least-squares refinement[9] on F was based on 24476 observed reflections ($I > 2.00\sigma(I)$) and 419 variable parameters and converged (largest parameter shift was 0.00 times its esd) with unweighted and weighted agreement factors of:

$$R = \Sigma \; ||Fo| - |Fc|| \; / \; \Sigma \; |Fo| = 0.0477$$

$$R_W = [\Sigma \; w \; (|Fo| - |Fc|)^2 \; / \; \Sigma \; w \; Fo^2]^{1/2} = 0.0580$$

The standard deviation of an observation of unit weight[10] was 1.00. A Chebychev polynomial weighting scheme was used.[11] Plots of Σ w $(|Fo|-|Fc|)^2$ versus |Fo|, reflection order in data collection, $\sin\theta/\lambda$ and various classes of indices showed no unusual trends. The maximum and minimum peaks on the final difference Fourier map corresponded to 1.80 and –1.66 $e^-/Å^3$, respectively. The absolute structure was deduced based on Flack parameter, –0.03(3), refined using 3368 Friedel pairs.[12]

Neutral atom scattering factors were taken from Cromer and Waber.[13] Anomalous dispersion effects were included in Fcalc;[14] the values for $\Delta f'$ and $\Delta f''$ were those of Creagh and McAuley.[15] The values for the mass attenuation coefficients are those of Creagh and

---

[7] SIR92: A. Altomare, G. Cascarano, C. Giacovazzo, A. Guagliardi, M. Burla, G. Polidori and M. Camalli, *J. Appl. Cryst.* 1994, **27**, 435.

[8] DIRDIF99: P. T. Beurskens, G. Admiraal, G. Beurskens, W. P. Bosman, R. de Gelder, R. Israel and J. M. M. Smits, The DIRDIF-99 program system, Technical Report of the Crystallography Laboratory, University of Nijmegen, The Netherlands (1999).

[9] Least Squares function minimized:

$\Sigma w(|F_O|-|F_C|)^2$ where w = Least Squares weights.

[10] Standard deviation of an observation of unit weight:

$[\Sigma w(|F_O|-|F_C|)^2/(N_O-N_V)]^{1/2}$

where: N_O = number of observations, N_V = number of variables

[11] J. R. Carruthers and D. J. Watkin, *Acta Crystallogr.* 1979, **A35**, 698.

[12] H. D. Flack, *Acta Crystallogr.* 1983, **A39**, 876.

[13] D. T. Cromer and J. T. Waber, "International Tables for X-ray Crystallography", Vol. IV, The Kynoch Press, Birmingham, England, Table 2.2 A (1974).

[14] J. A. Ibers and W. C. Hamilton, *Acta Crystallogr.* 1964, **17**, 781.

[15] D. C. Creagh and W. J. McAuley, "International Tables for Crystallography", Vol C, (A. J. C. Wilson, ed.), Kluwer Academic Publishers, Boston, Table 4.2.6.8, pages 219–222 (1992).

Hubbell.[16] All calculations were performed using the CrystalStructure[17,18] crystallographic software package.

The crystal structure has been deposited at the Cambridge Crystallographic Data Centre (deposition number: CCDC 775043). The data can be obtained free of charge via the Internet at www.ccdc.cam.ac.uk/conts/retrieving.html.

[16] D. C. Creagh and J. H. Hubbell, "International Tables for Crystallography", Vol C, (A. J. C. Wilson, ed.), Kluwer Academic Publishers, Boston, Table 4.2.4.3, pages 200–206 (1992).

[17] CrystalStructure 3.8: Crystal Structure Analysis Package, Rigaku and Rigaku Americas (2000-2007). 9009 New Trails Dr. The Woodlands TX 77381 USA.

[18] CRYSTALS Issue 11: J. R. Carruthers, J. S. Rollett, P. W. Betteridge, D. Kinna, L. Pearce, A. Larsen and E. Gabe, Chemical Crystallography Laboratory, Oxford, UK (1999).

Experimental Details

A. Crystal Data

Empirical Formula	$C_{36}H_{30}O_3N_2ClF$
Formula Weight	593.10
Crystal Color, Habit	colorless, prism
Crystal Dimensions	0.40 X 0.30 X 0.30 mm
Crystal System	tetragonal
Lattice Type	Primitive
Indexing Images	3 oscillations @ 30.0 seconds
Detector Position	127.40 mm
Pixel Size	0.100 mm
Lattice Parameters	a = 9.339(2) Å c = 34.336(6) Å V = 2994.8(10) Å^3
Space Group	$P4_3$ (#78)
Z value	4
D_{calc}	1.315 g/cm^3
F_{000}	1240.00
μ(MoKα)	1.733 cm^{-1}

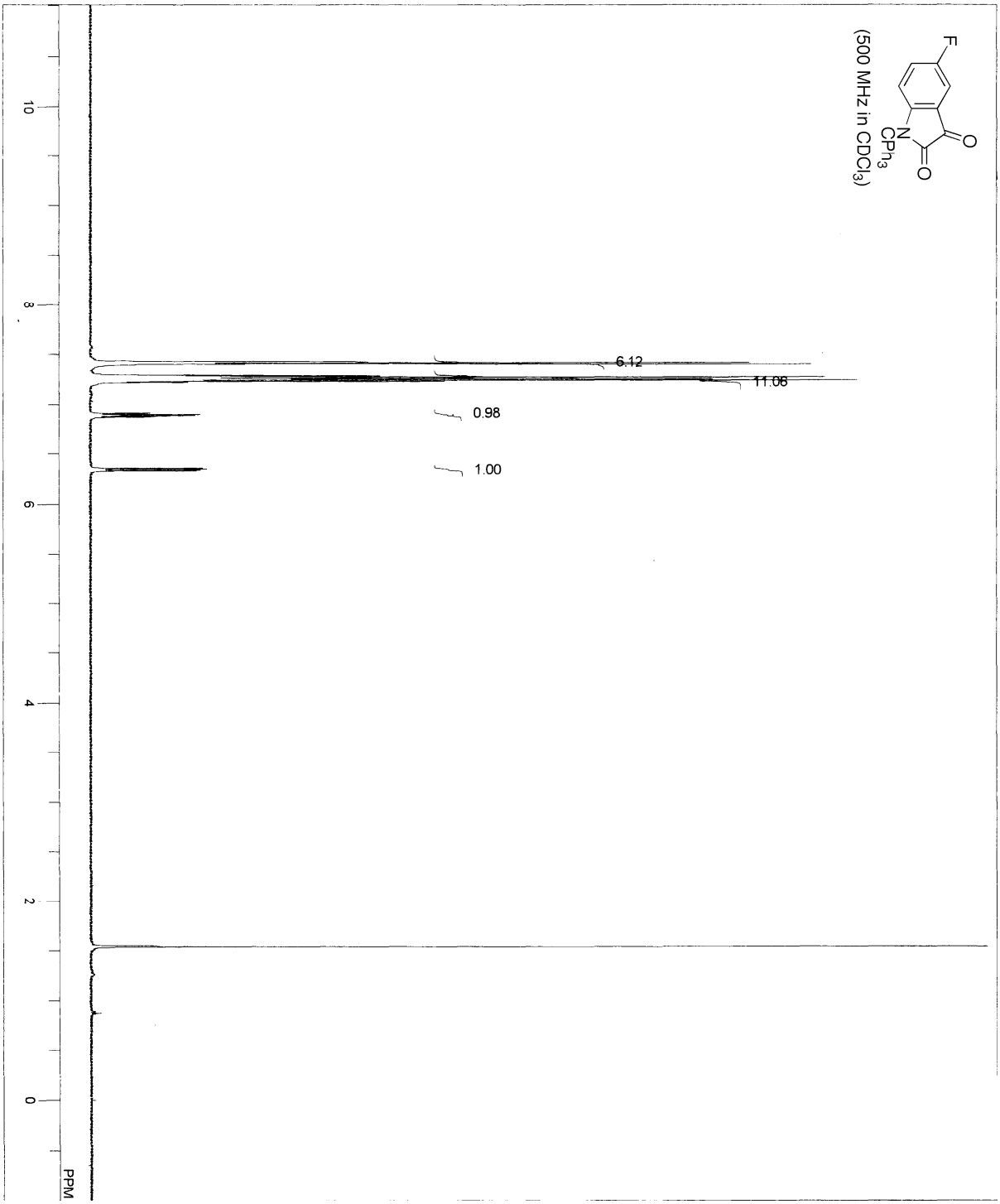
B. Intensity Measurements

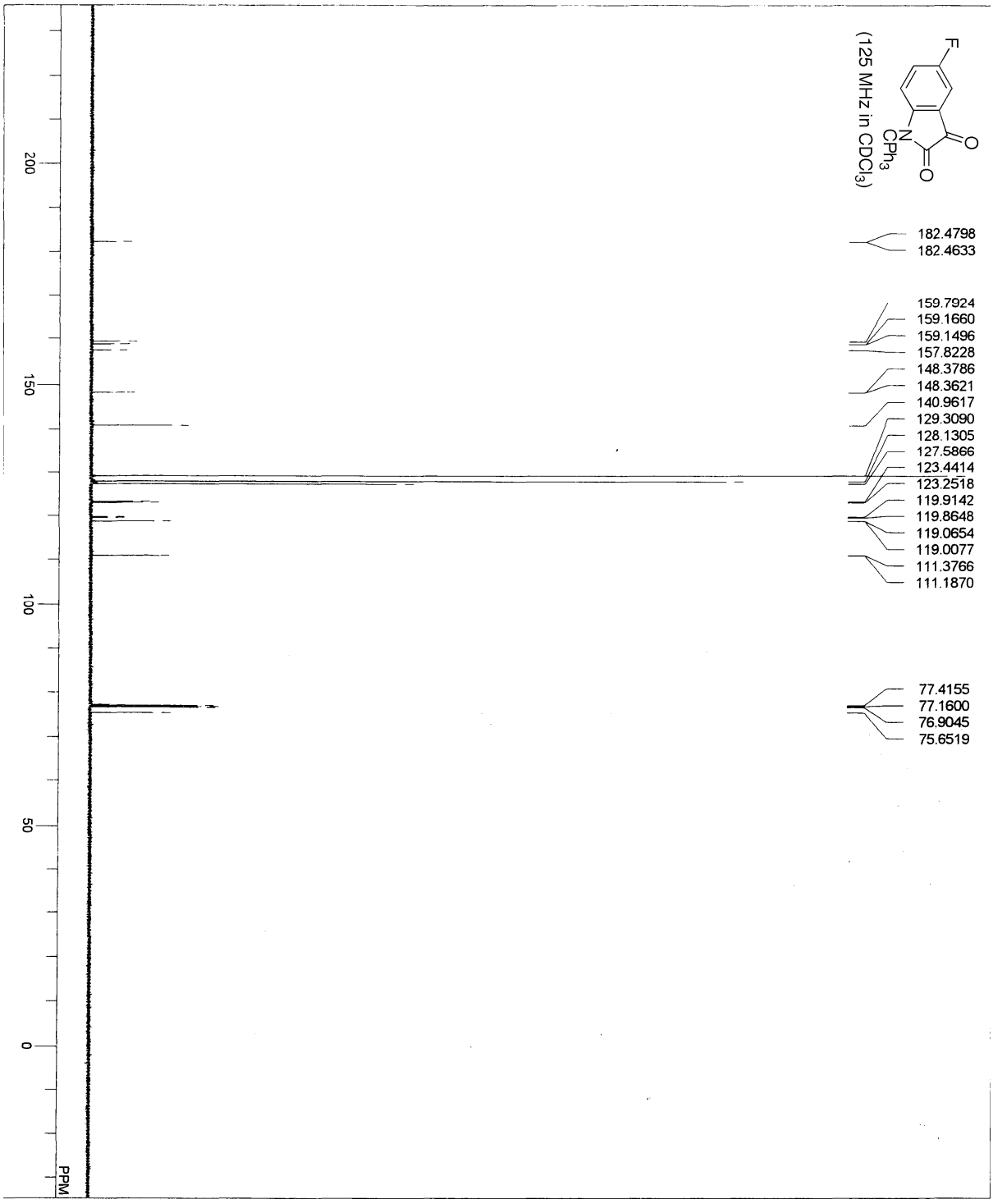
Diffractometer	Rigaku RAXIS-RAPID
Radiation	MoKα (λ = 0.71075 Å) graphite monochromated
Detector Aperture	280 mm x 256 mm
Data Images	44 exposures
ω oscillation Range (χ=45.0, ϕ=30.0)	130.0 - 190.0°
Exposure Rate	80.0 sec./°
ω oscillation Range (χ=45.0, ϕ=180.0)	0.0 - 160.0°
Exposure Rate	80.0 sec./°
Detector Position	127.40 mm
Pixel Size	0.100 mm
$2\theta_{max}$	55.0°
No. of Reflections Measured	Total: 29293 Unique: 6852 (R_{int} = 0.050) Friedel pairs: 3368
Corrections	Lorentz-polarization

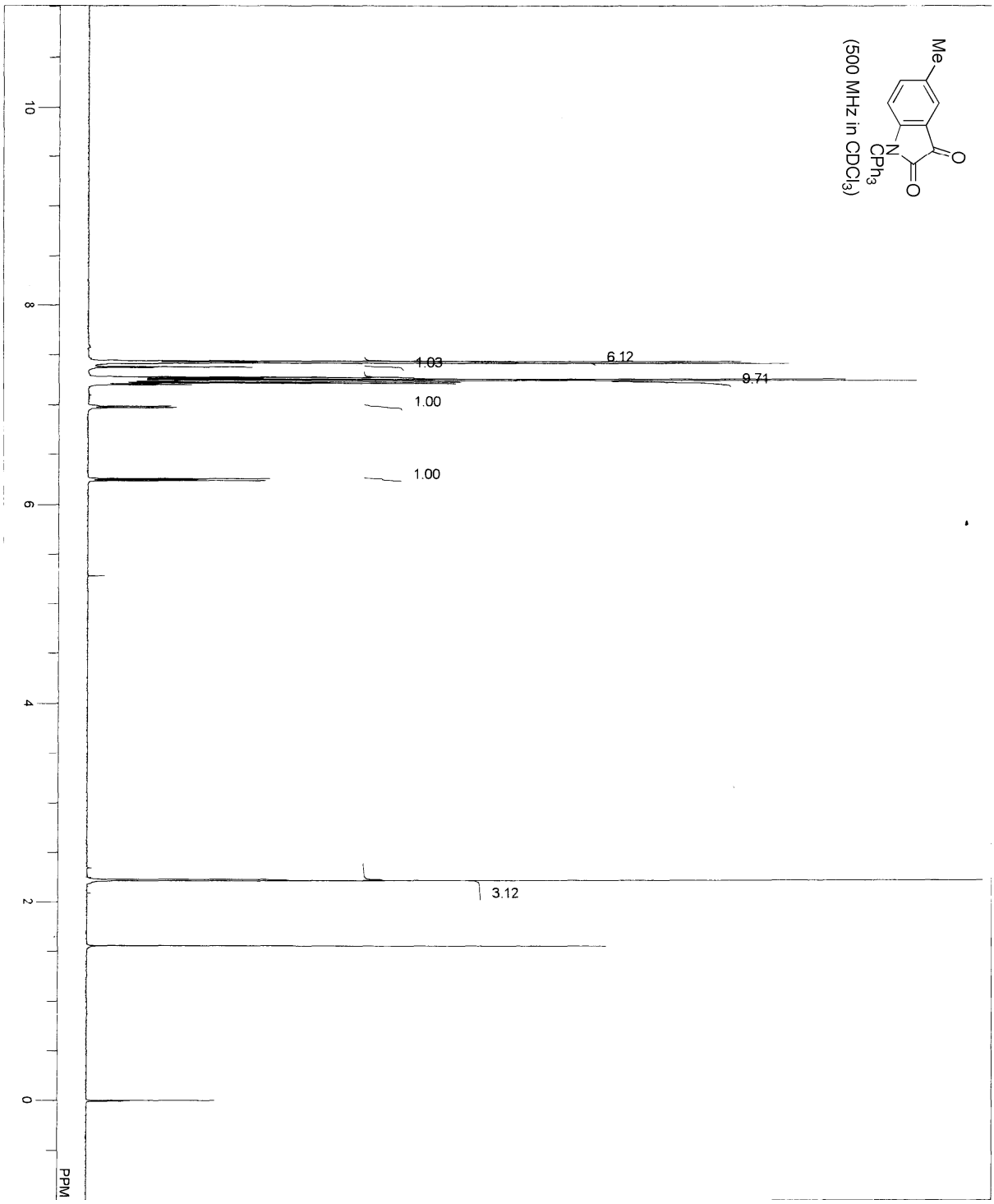
C. Structure Solution and Refinement

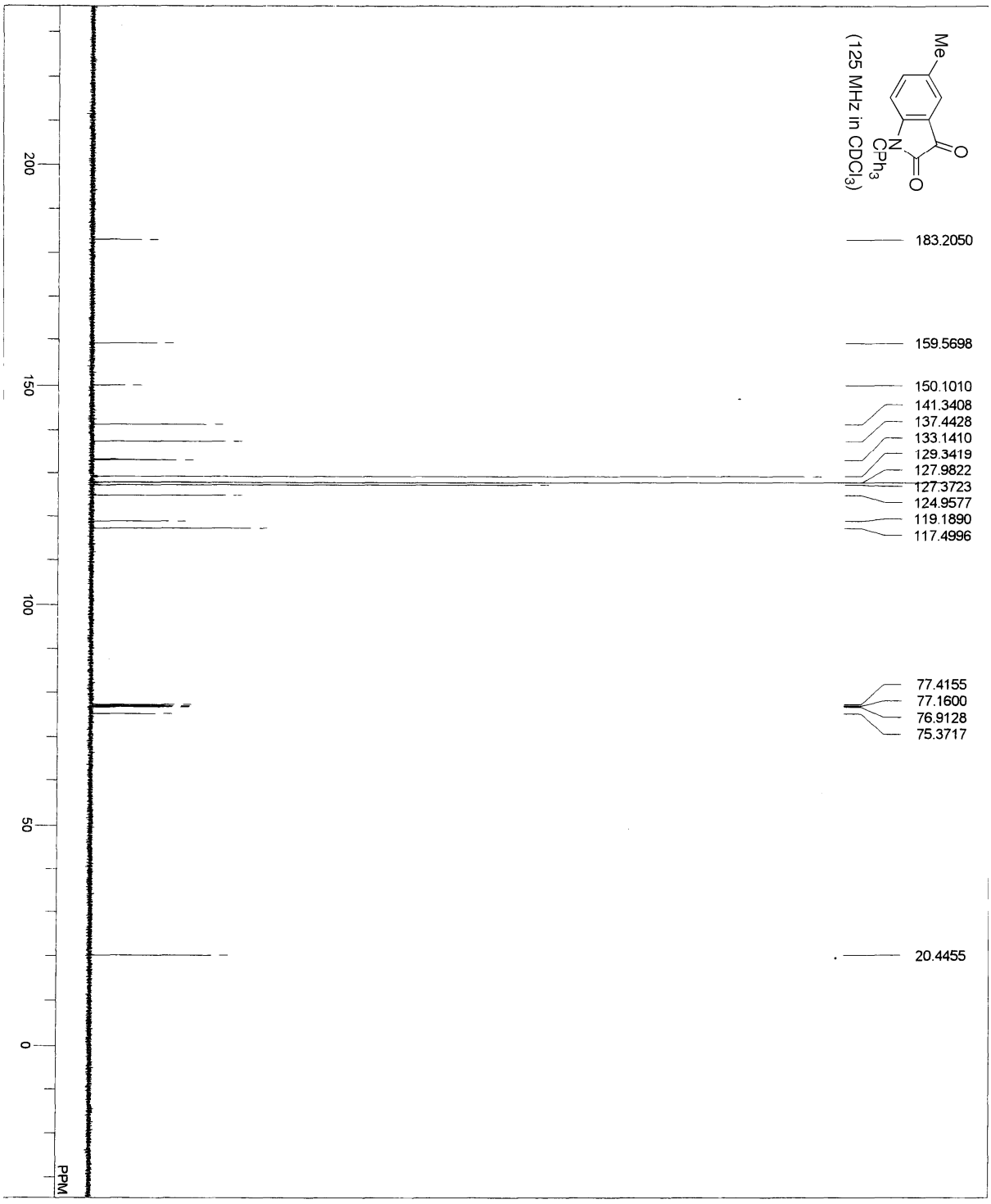
Structure Solution	Direct Methods (SIR92)
Refinement	Full-matrix least-squares on F
Function Minimized	Σ w (|Fo| –|Fc|)^2
Least Squares Weights	Chebychev polynomial with 3 parameters 26.3839, 24.6720, 7.9365
$2\theta_{max}$ cutoff	55.0°
Anomalous Dispersion	All non-hydrogen atoms
No. Observations (I>2.00σ(I))	24476
No. Variables	419
Reflection/Parameter Ratio	58.42
Residuals: R (I>2.00σ(I))	0.0477
Residuals: Rw (I>2.00σ(I))	0.0580
Goodness of Fit Indicator	1.004
Flack parameter	–0.03(3)
Max Shift/Error in Final Cycle	0.000
Maximum peak in Final Diff. Map	1.80 e^-/Å^3
Minimum peak in Final Diff. Map	–1.66 e^-/Å^3

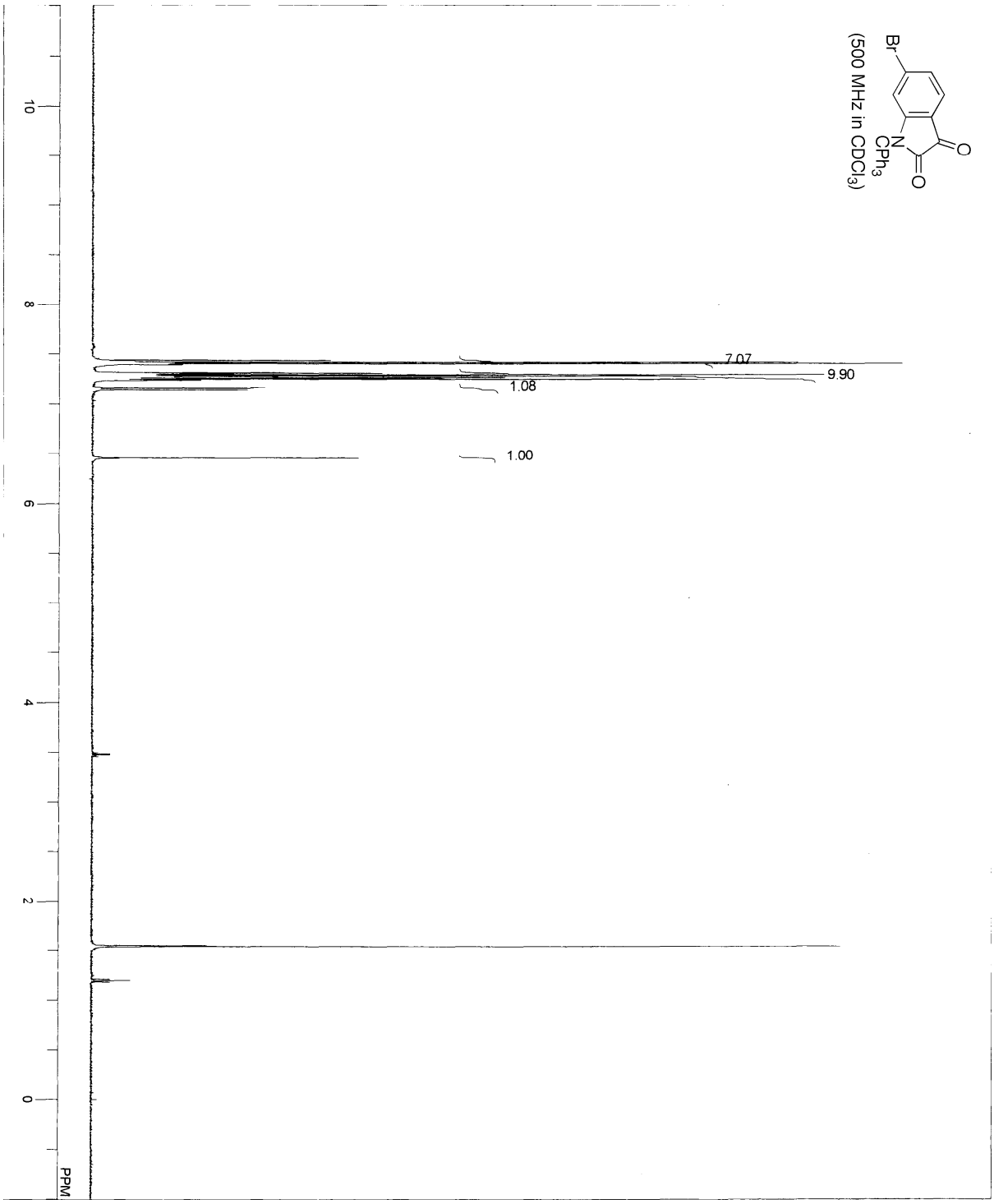
VI. ^{1}H and ^{13}C NMR Spectra

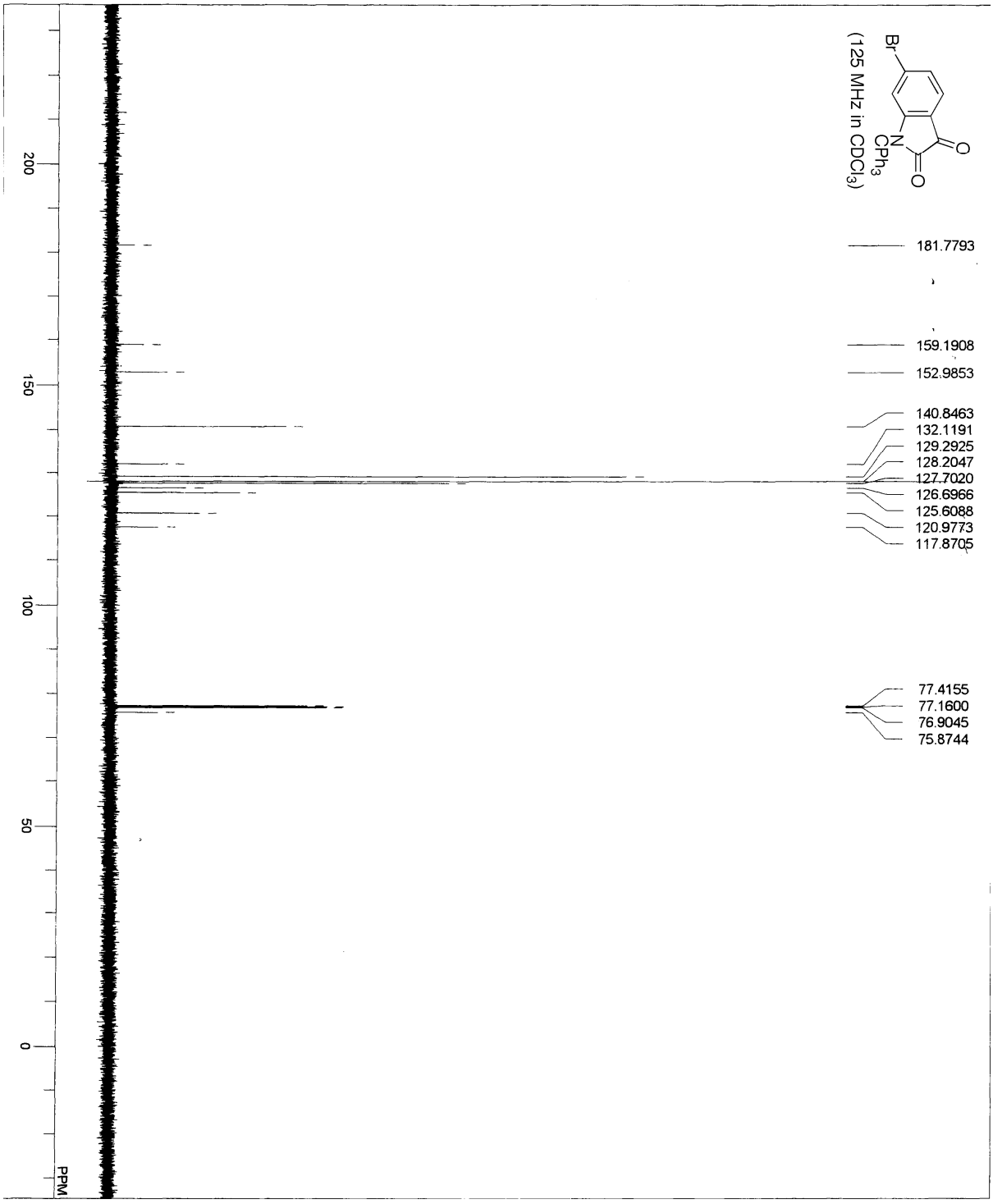


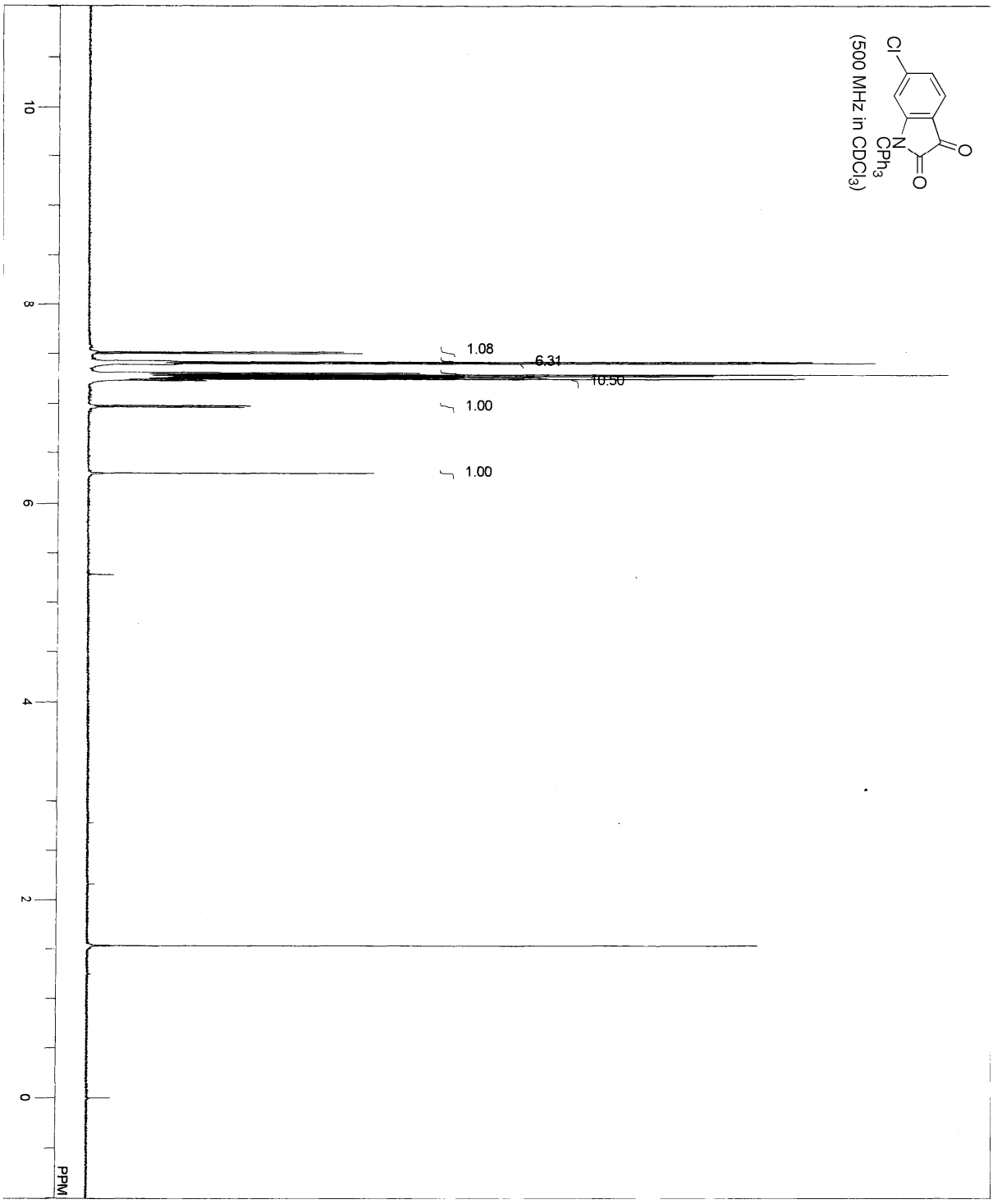

(125 MHz in CDCl3)
F
N
CPh3
O
O
182.4798
182.4633
159.7924
159.1660
159.1496
157.8228
148.3786
148.3621
140.9617
129.3090
128.1305
127.5866
123.4414
123.2518
119.9142
119.8648
119.0654
119.0077
111.3766
111.1870
77.4155
77.1600
76.9045
75.6519
200
150
100
50
0
PPM

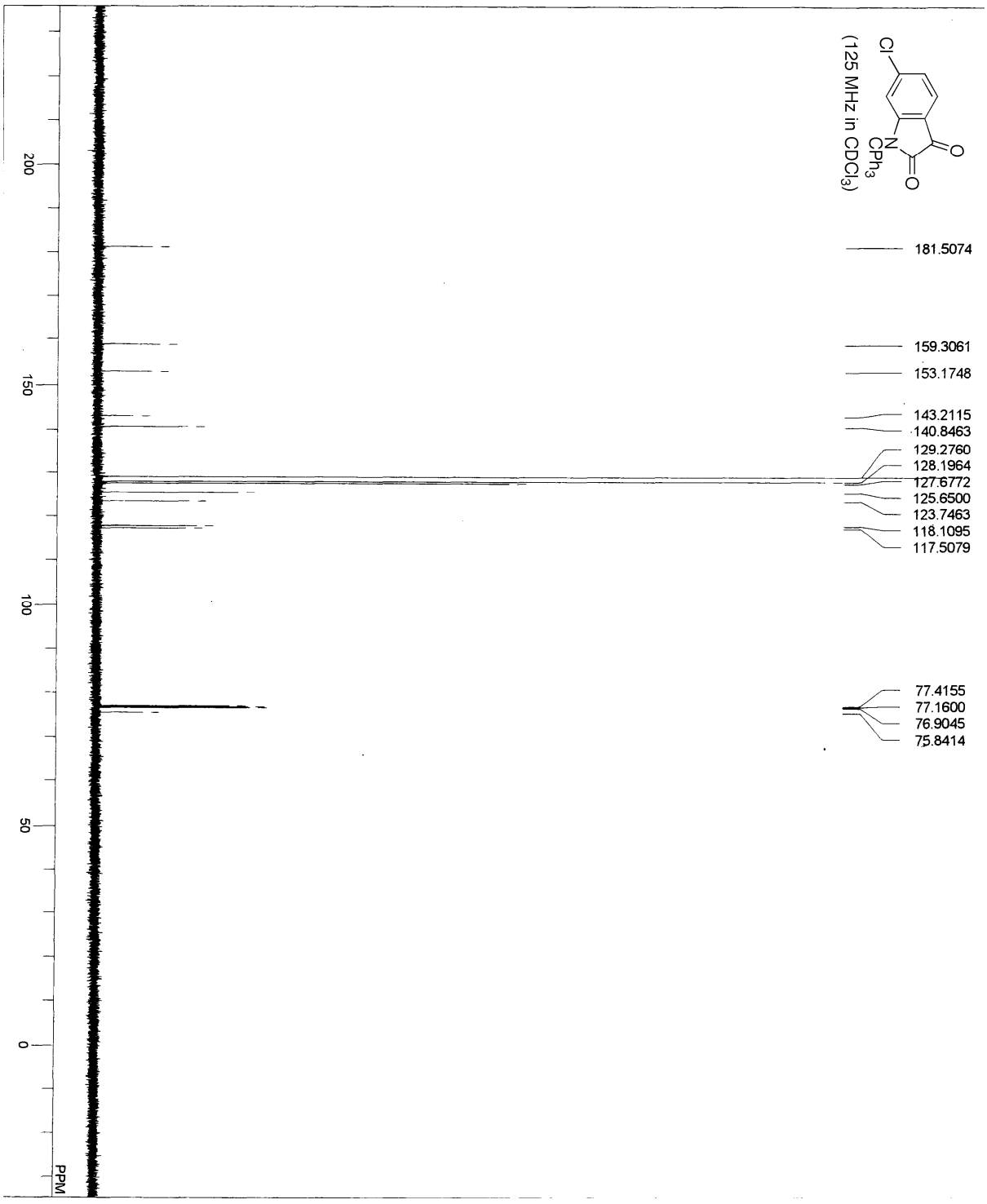

Me
O
N
CPh3
O
(500 MHz in CDCl3)
10
8
6
4
2
0
PPM
1.03
6.12
9.71
1.00
1.00
3.12

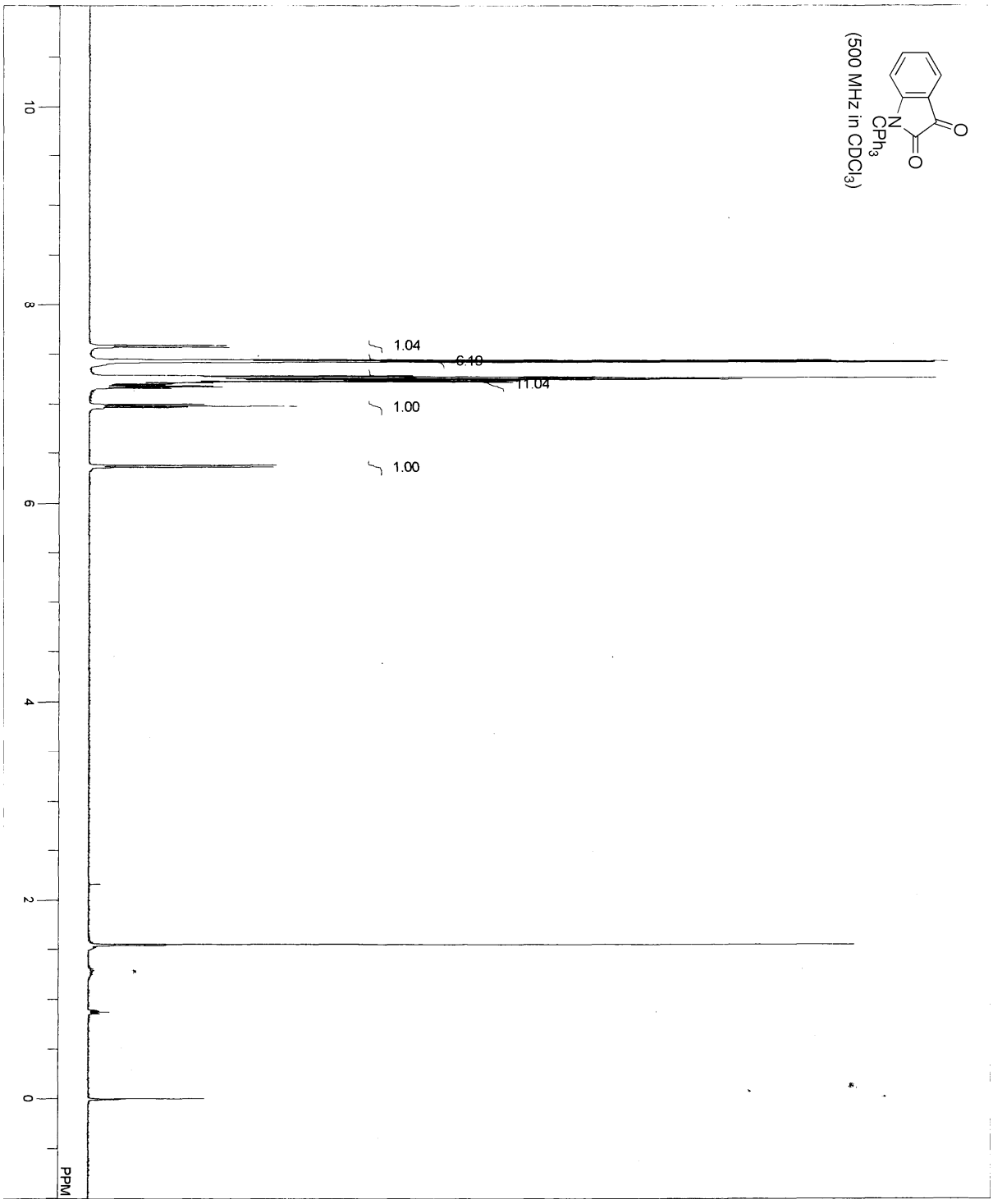

(125 MHz in CDCl3)
Me
N
CPh3
O
O
183.2050
159.5698
150.1010
141.3408
137.4428
133.1410
129.3419
127.9822
127.3723
124.9577
119.1890
117.4996
77.4155
77.1600
76.9128
75.3717
20.4455
200
150
100
50
0
PPM

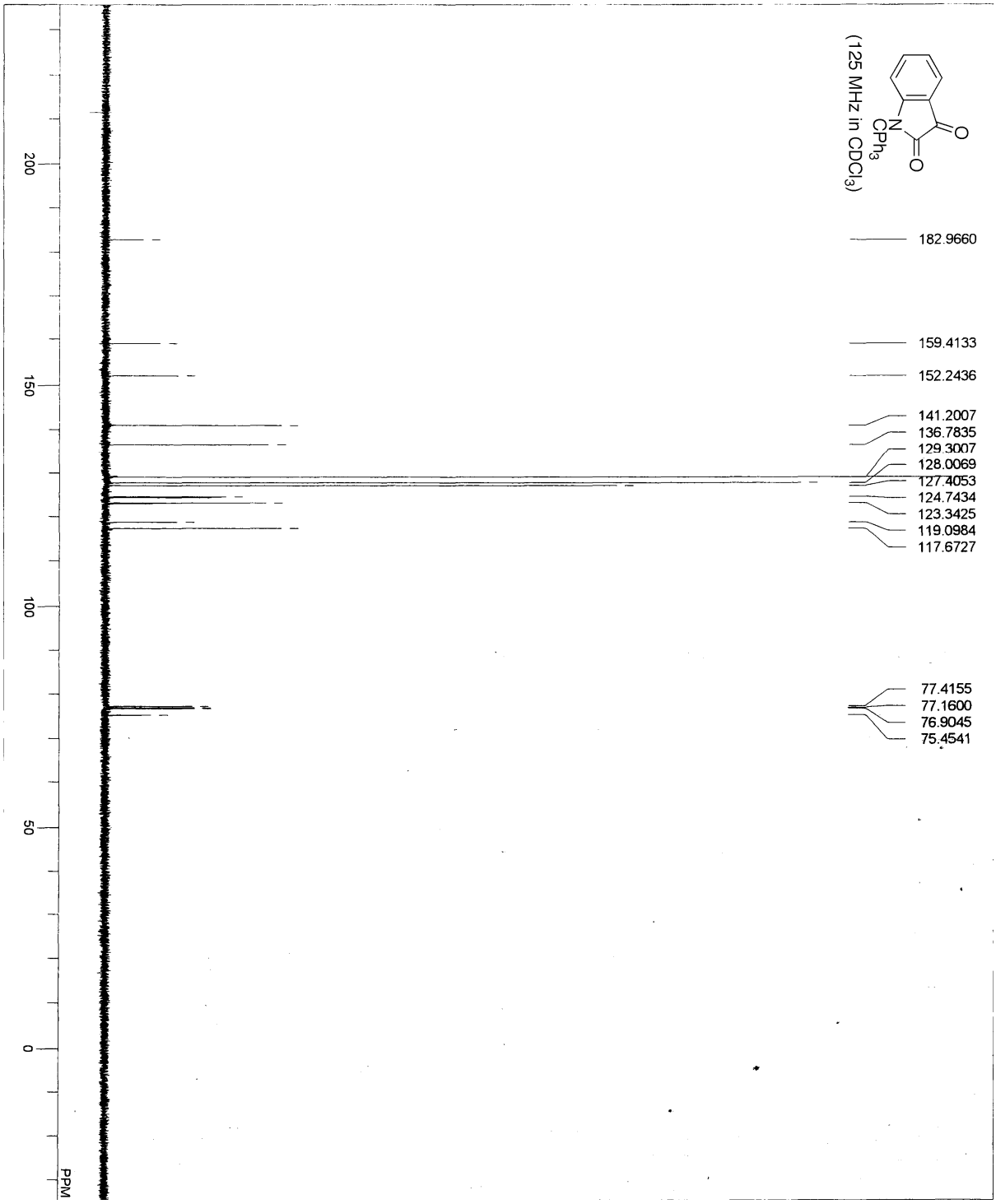

Br
N
CPh3
O
O
(500 MHz in CDCl3)
7.07
9.90
1.08
1.00
10
8
6
4
2
0
PPM

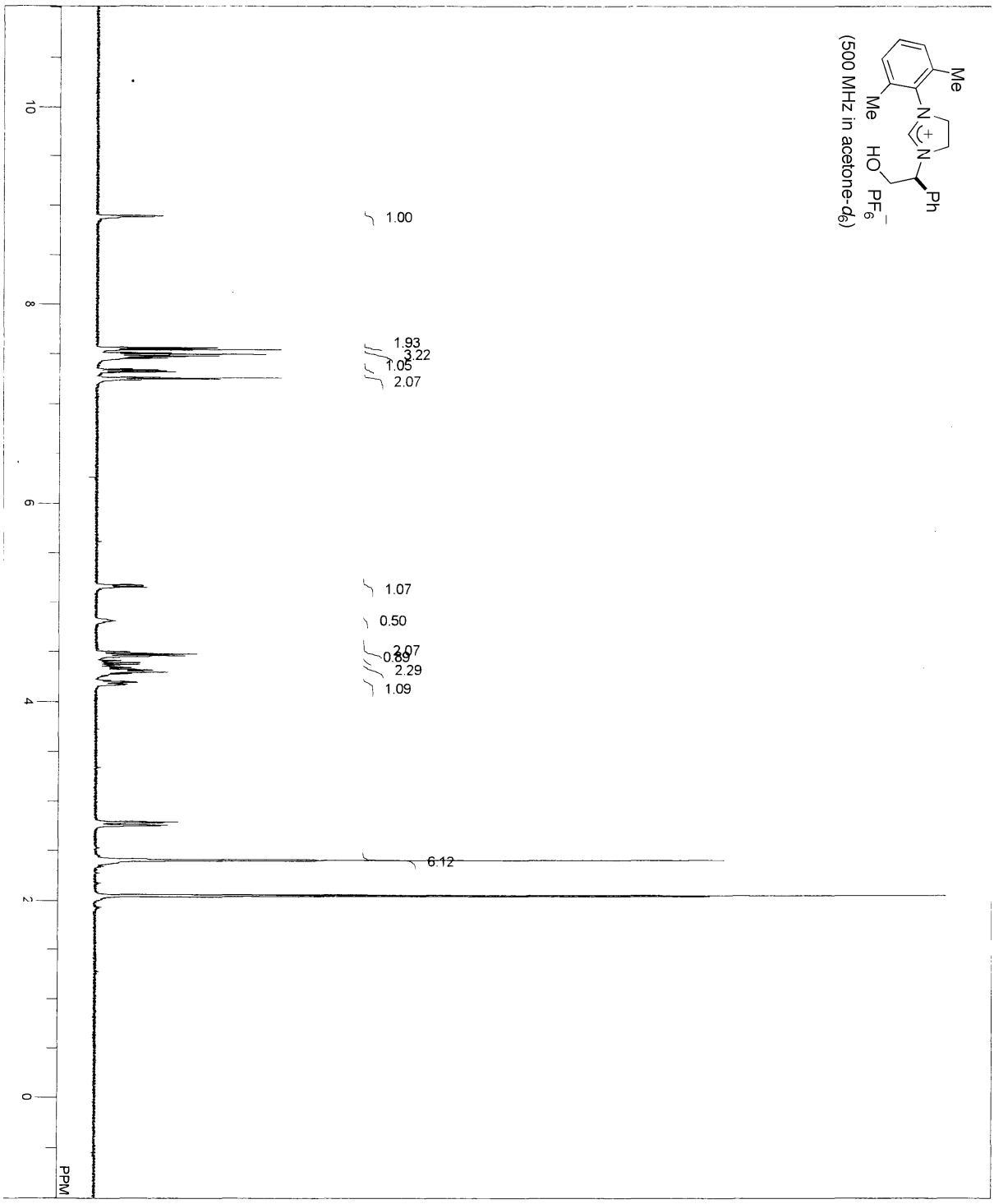

(125 MHz in CDCl3)
Br
N
CPh3
O
O
181.7793
159.1908
152.9853
140.8463
132.1191
129.2925
128.2047
127.7020
126.6966
125.6088
120.9773
117.8705
77.4155
77.1600
76.9045
75.8744
200
150
100
50
0
PPM

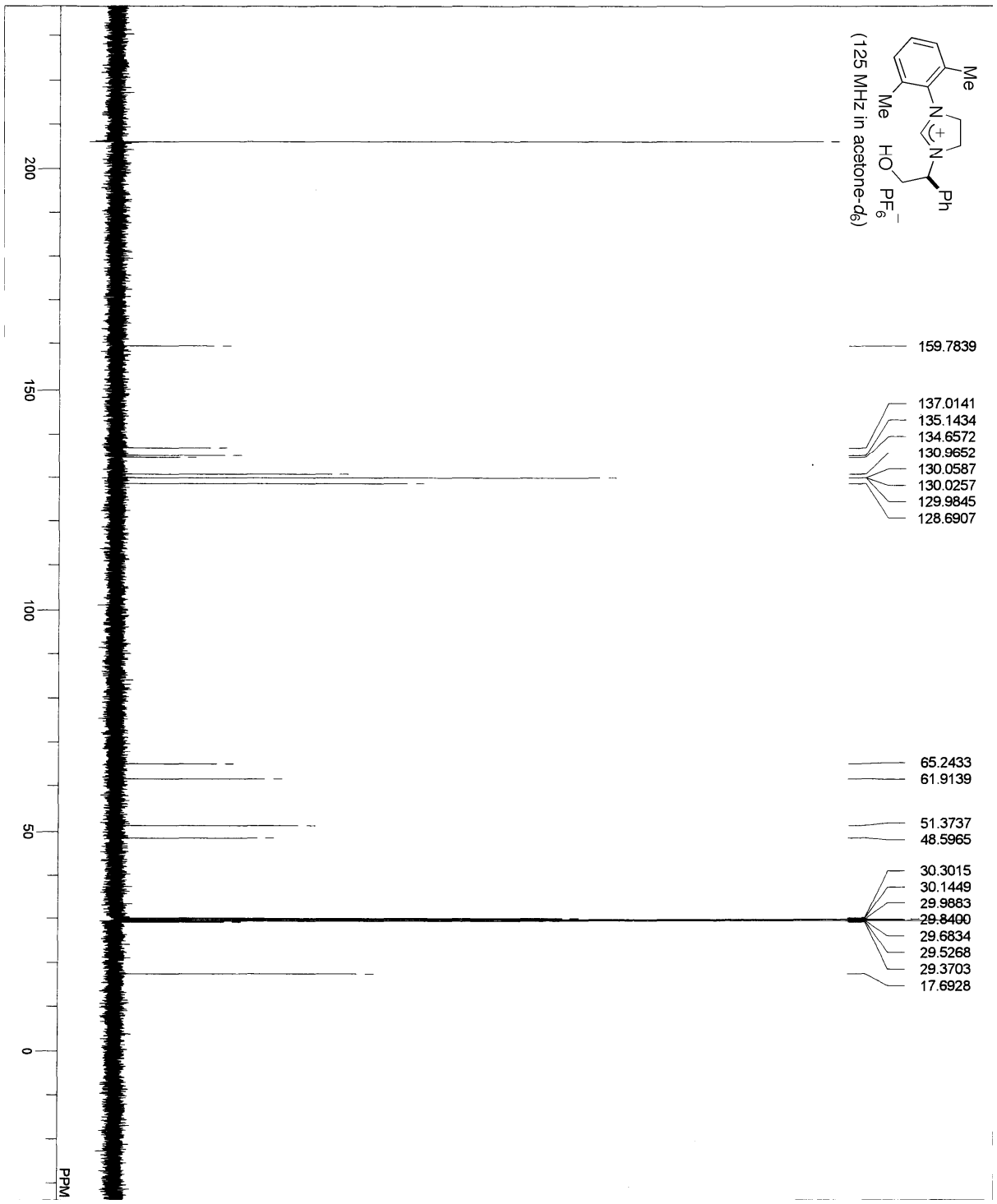

(500 MHz in CDCl3)
Cl
N
CPh3
O
O
1.08
6.31
10.50
1.00
1.00
10
8
6
4
2
0
PPM

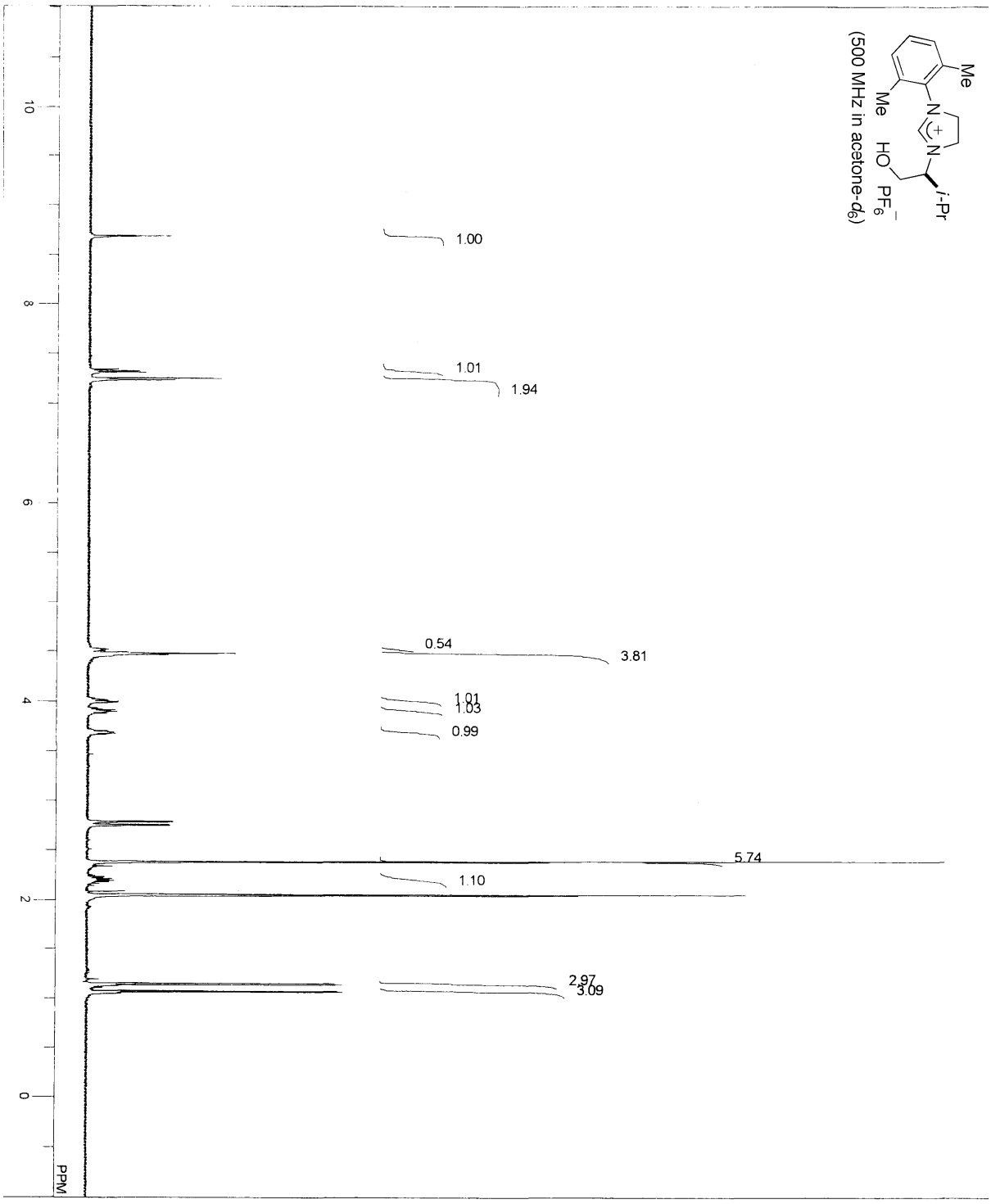

(125 MHz in CDCl3)
Cl
N
CPh3
O
O
181.5074
159.3061
153.1748
143.2115
140.8463
129.2760
128.1964
127.6772
125.6500
123.7463
118.1095
117.5079
77.4155
77.1600
76.9045
75.8414
200
150
100
50
0
PPM

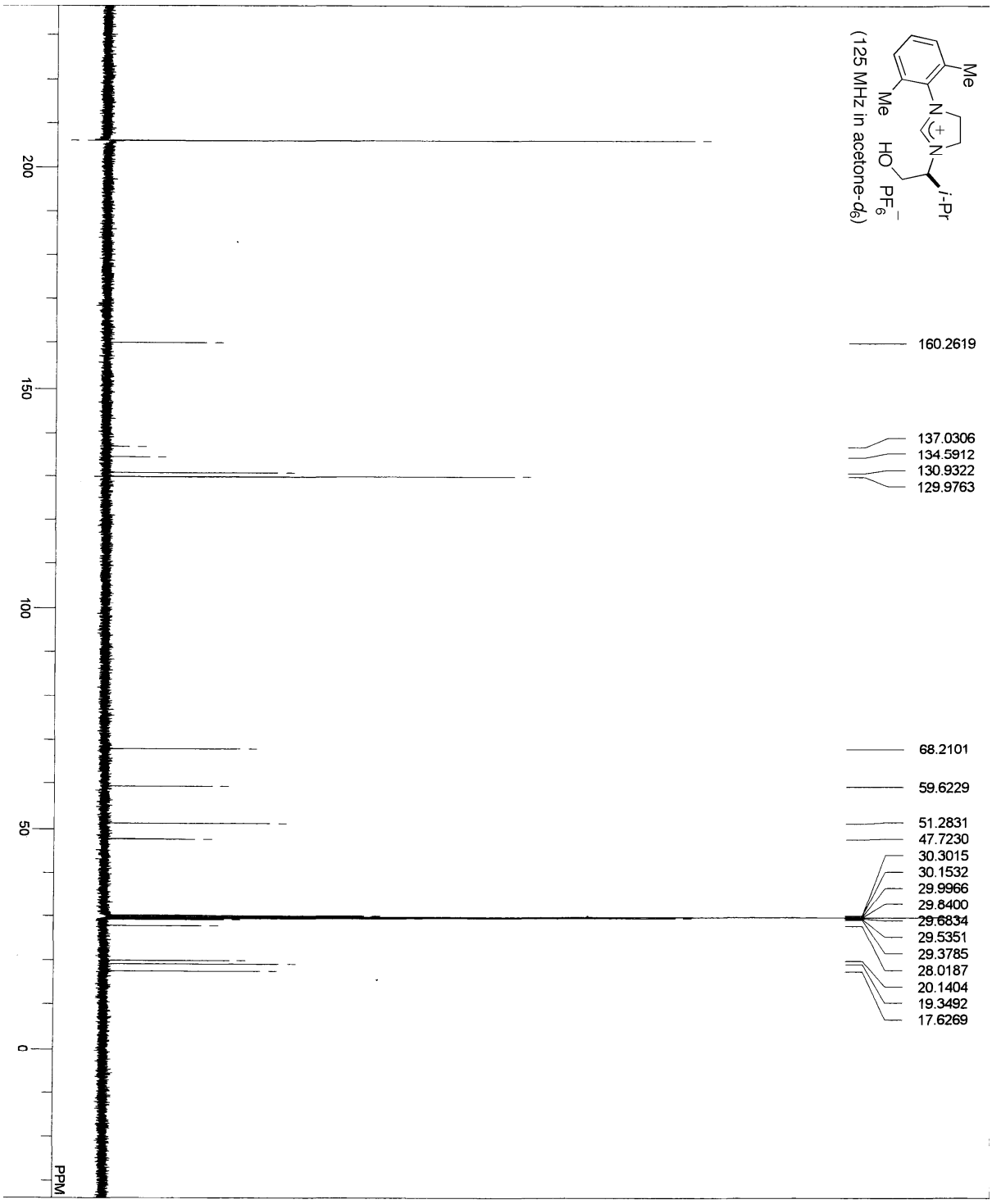

(500 MHz in CDCl3)
CPh3
N
O
O
1.04
6.19
11.04
1.00
1.00
10
8
6
4
2
0
PPM

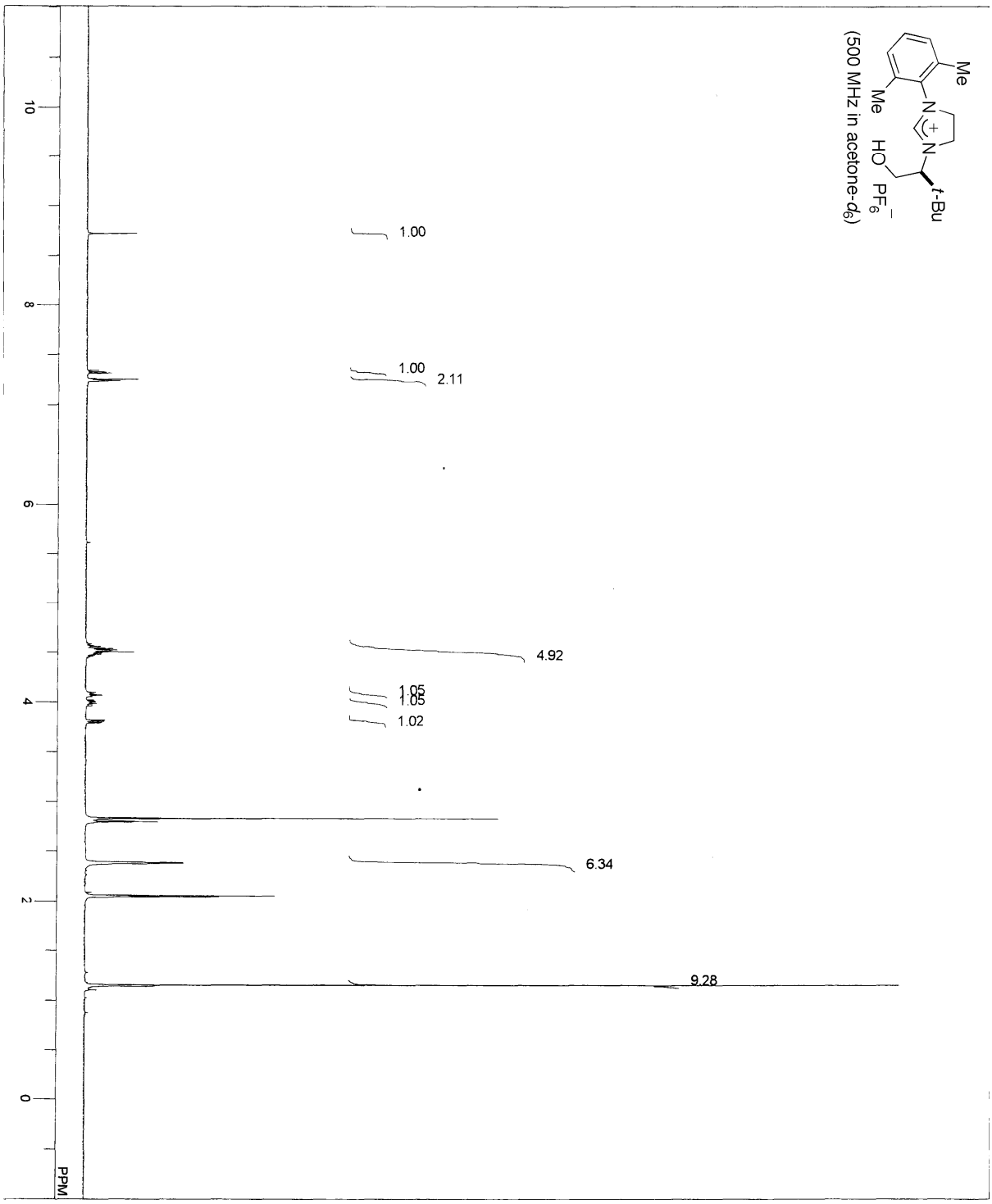

(125 MHz in CDCl3)
CPh3
N
O
O
182.9660
159.4133
152.2436
141.2007
136.7835
129.3007
128.0069
127.4053
124.7434
123.3425
119.0984
117.6727
77.4155
77.1600
76.9045
75.4541
200
150
100
50
0
PPM

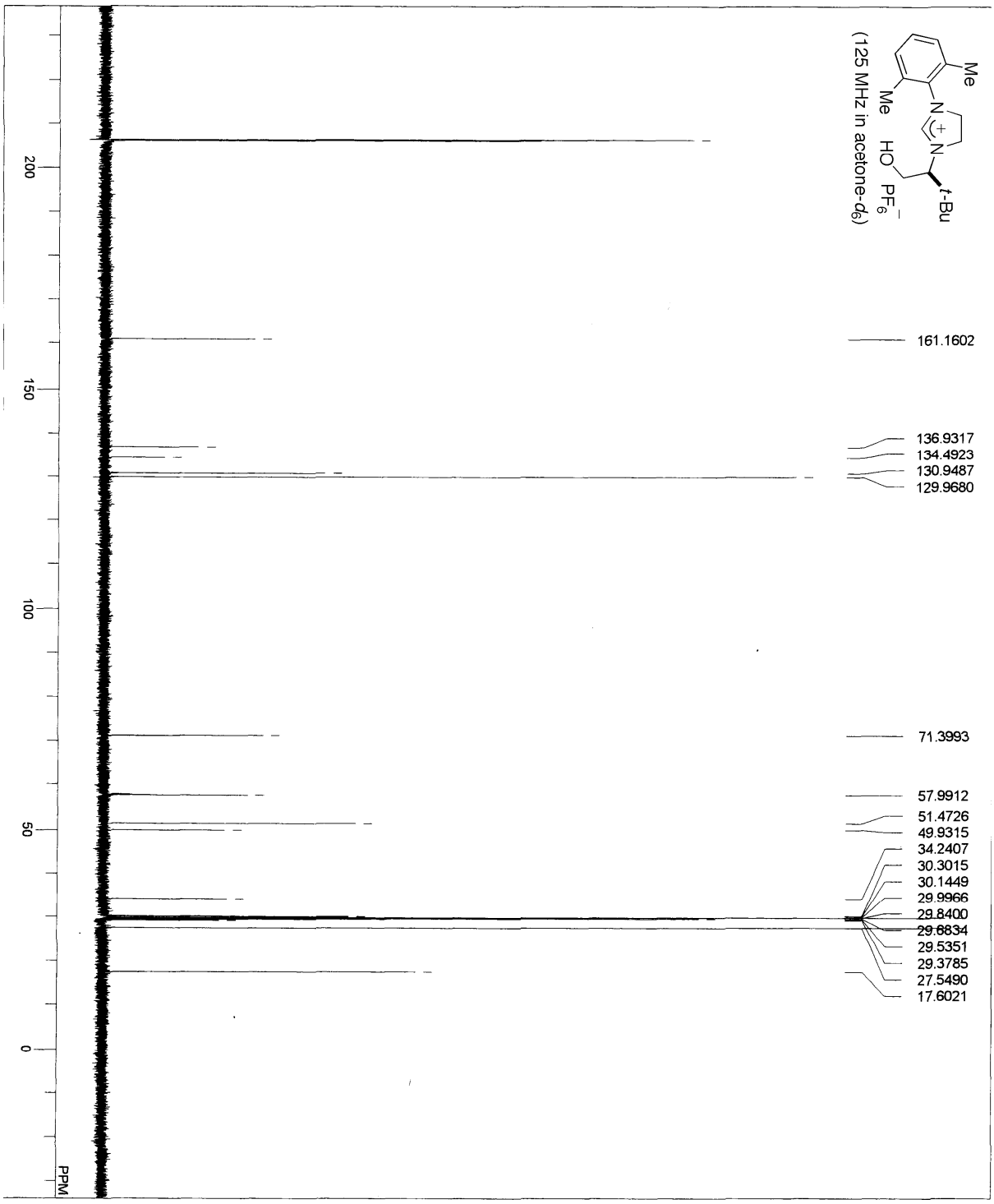

Me
Me
HO
Ph
PF_6^-
(500 MHz in acetone-d_6)
1.00
1.93
3.22
1.05
2.07
1.07
0.50
2.07
0.89
2.29
1.09
6.12
10
8
6
4
2
0
PPM

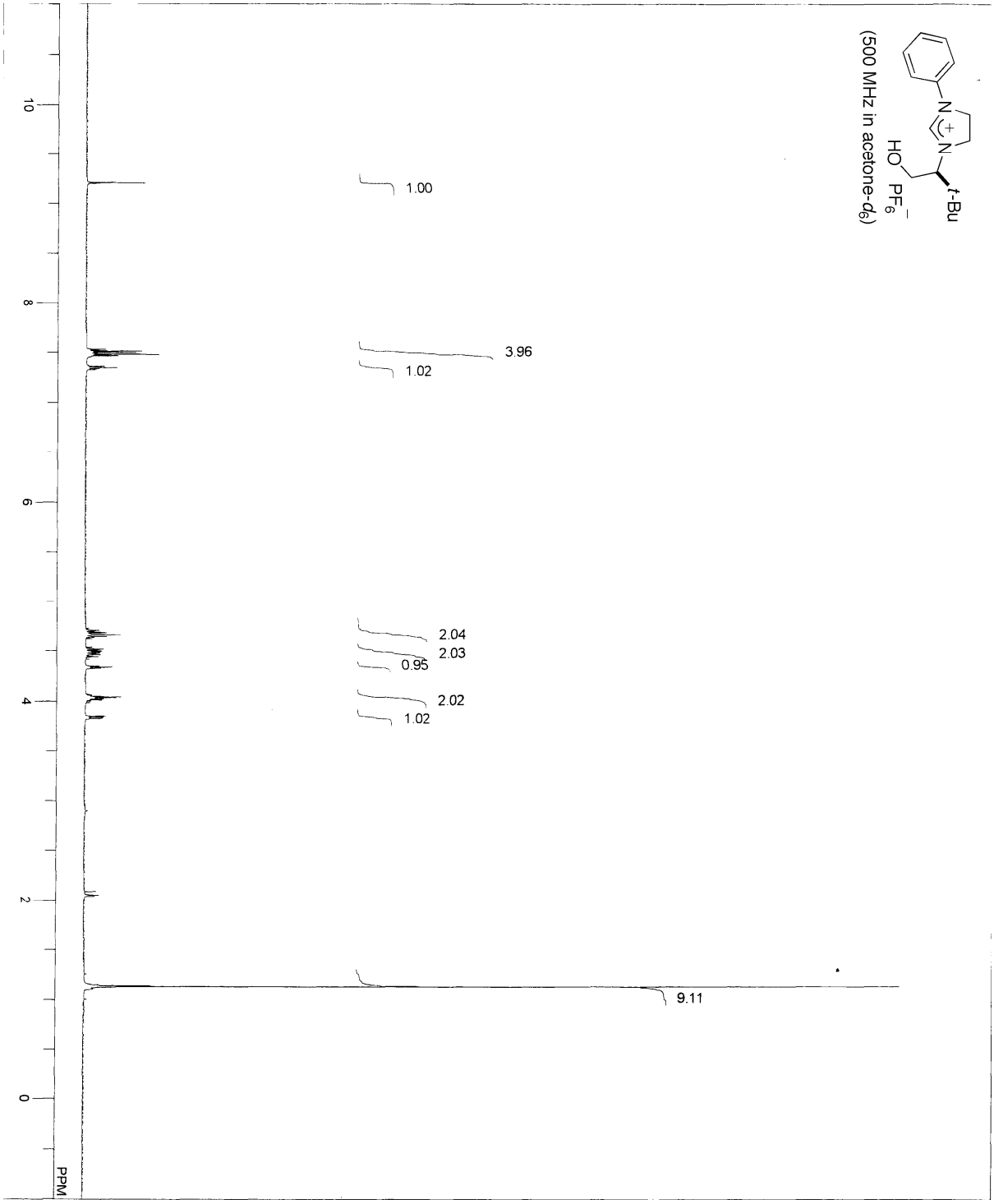

Me
Me
HO
PF6−
Ph
(125 MHz in acetone-d6)
159.7839
137.0141
135.1434
134.6572
130.9652
130.0587
130.0257
129.9845
128.6907
65.2433
61.9139
51.3737
48.5965
30.3015
30.1449
29.9883
29.8400
29.6834
29.5268
29.3703
17.6928
200
150
100
50
0
PPM

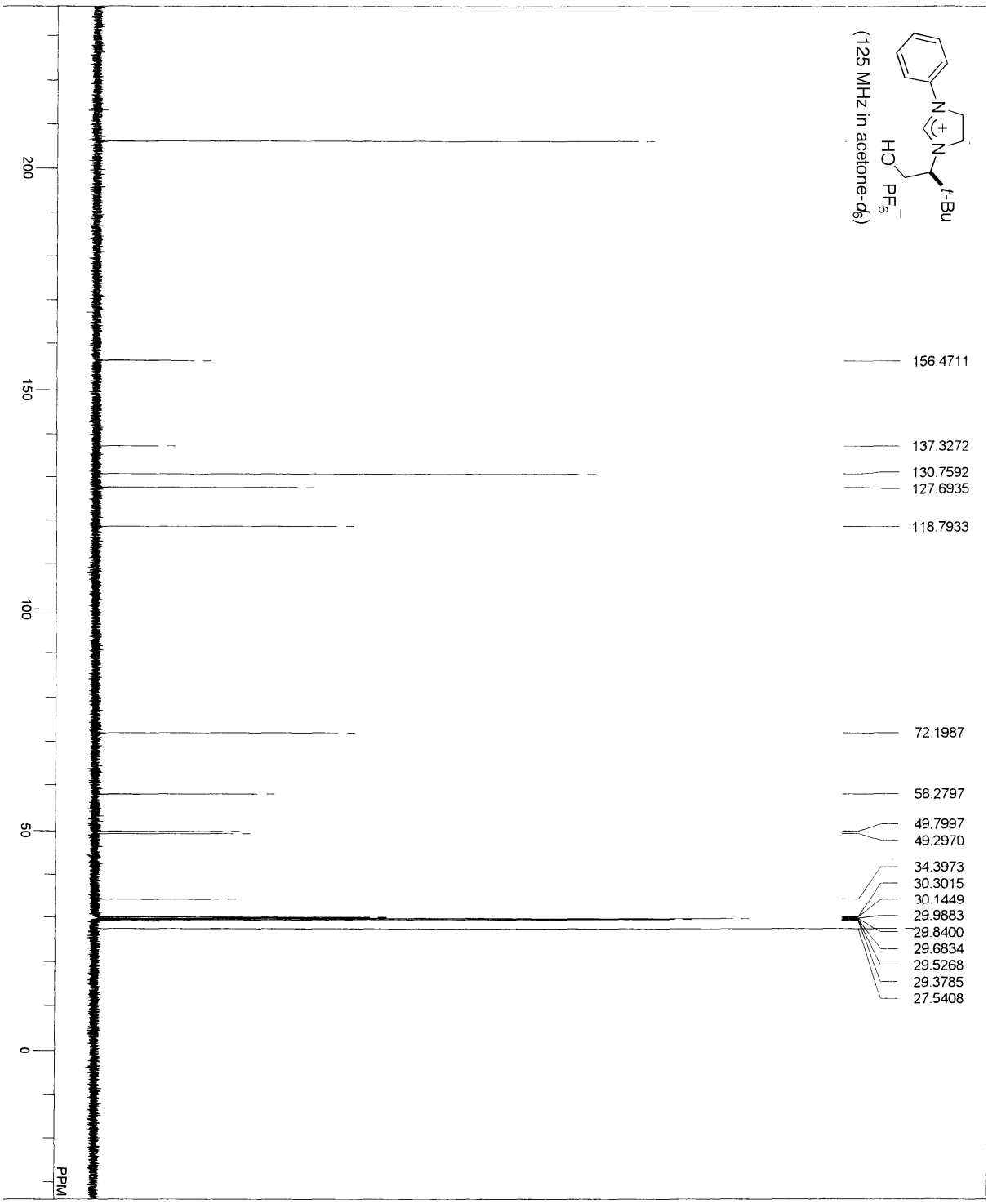

Me
Me
HO
PF6−
i-Pr
(500 MHz in acetone-d6)
1.00
1.01
1.94
0.54
3.81
1.01
1.03
0.99
5.74
1.10
2.97
3.09
10
8
6
4
2
0
PPM

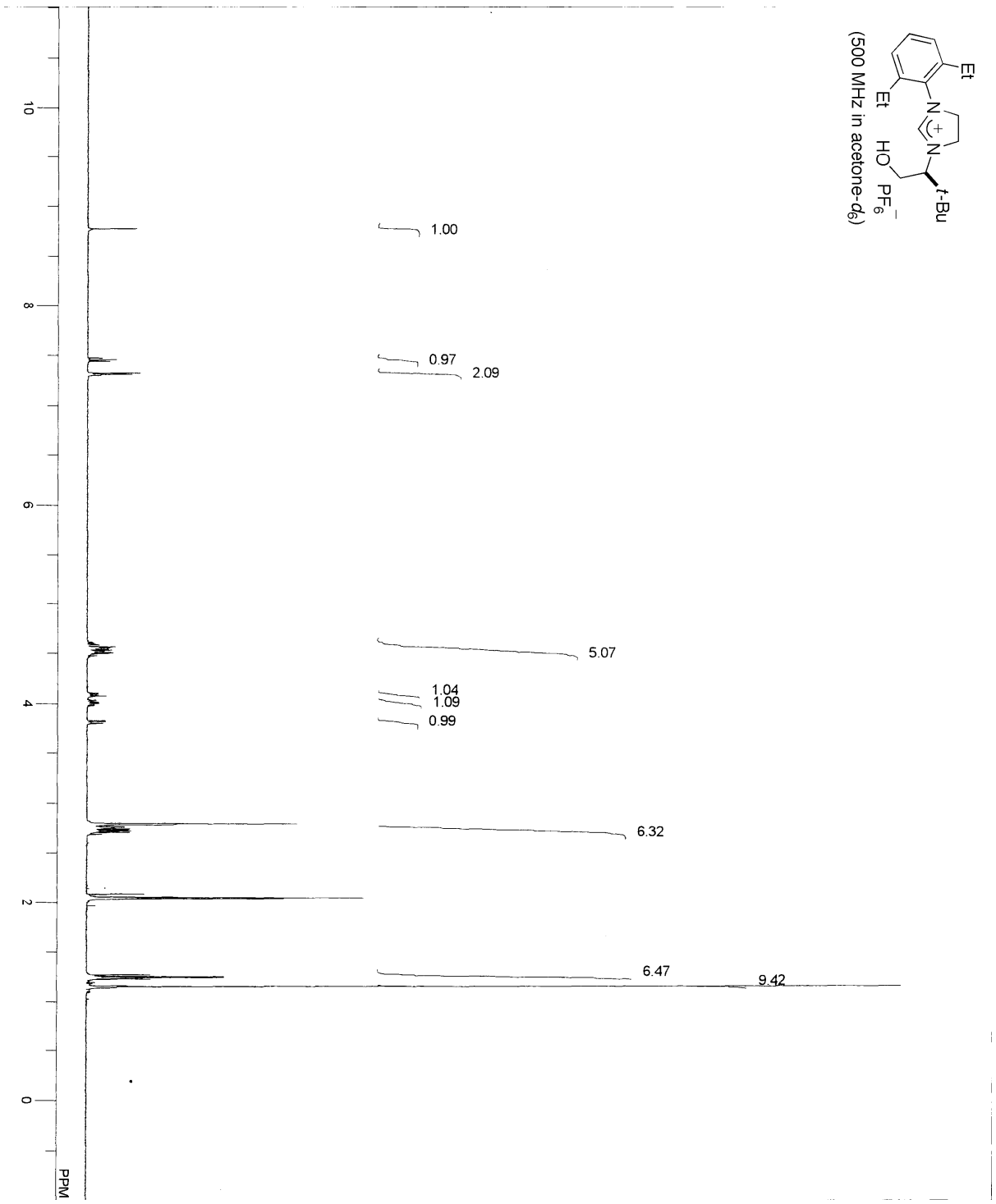

Me
Me
HO
PF6−
i-Pr
(125 MHz in acetone-d6)
160.2619
137.0306
134.5912
130.9322
129.9763
68.2101
59.6229
51.2831
47.7230
30.3015
30.1532
29.9966
29.8400
29.6834
29.5351
29.3785
28.0187
20.1404
19.3492
17.6269
200
150
100
50
0
PPM

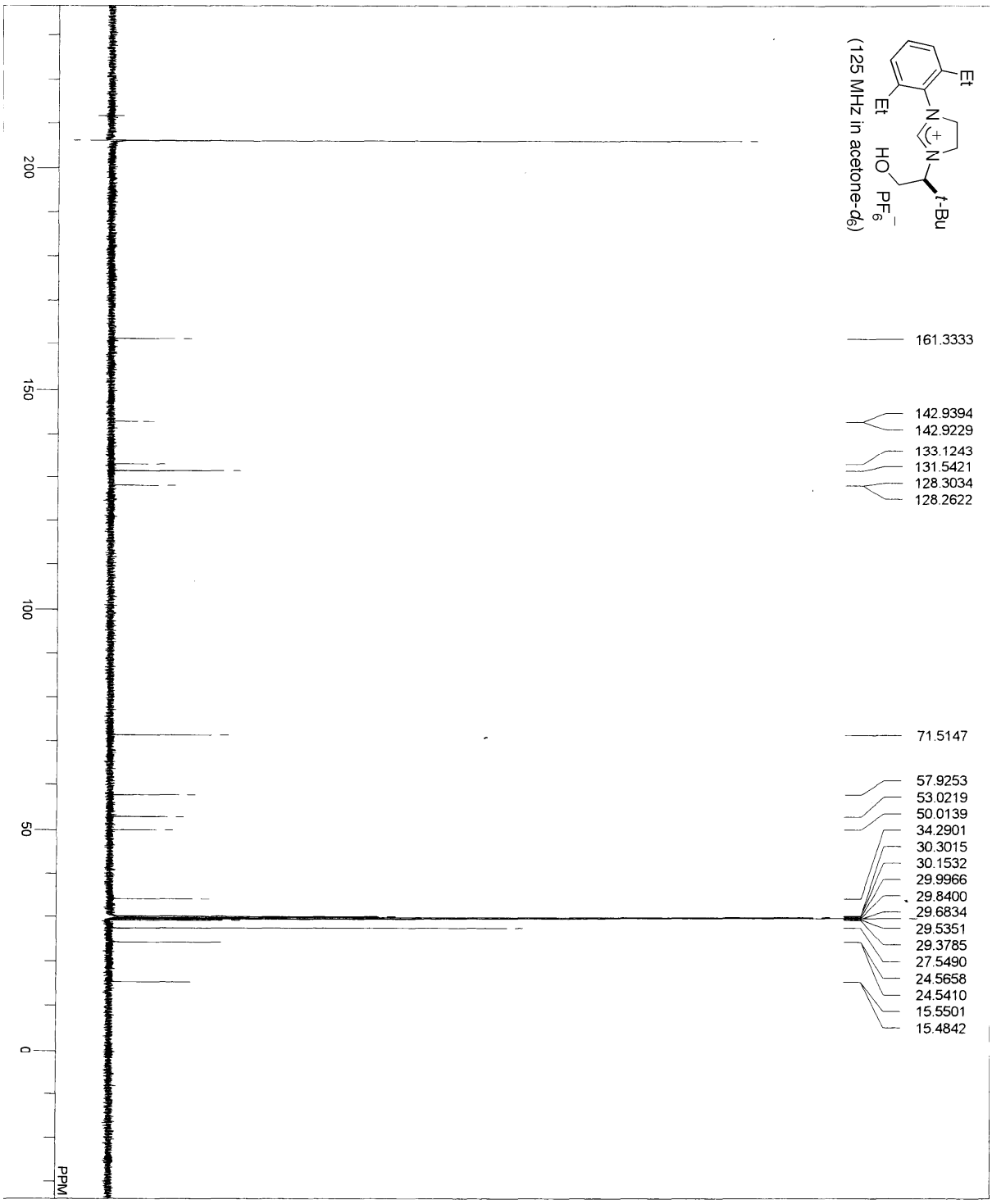

Me
Me
HO
PF6−
t-Bu
(500 MHz in acetone-d6)
1.00
1.00
2.11
4.92
1.05
1.05
1.02
6.34
9.28
10
8
6
4
2
0
PPM

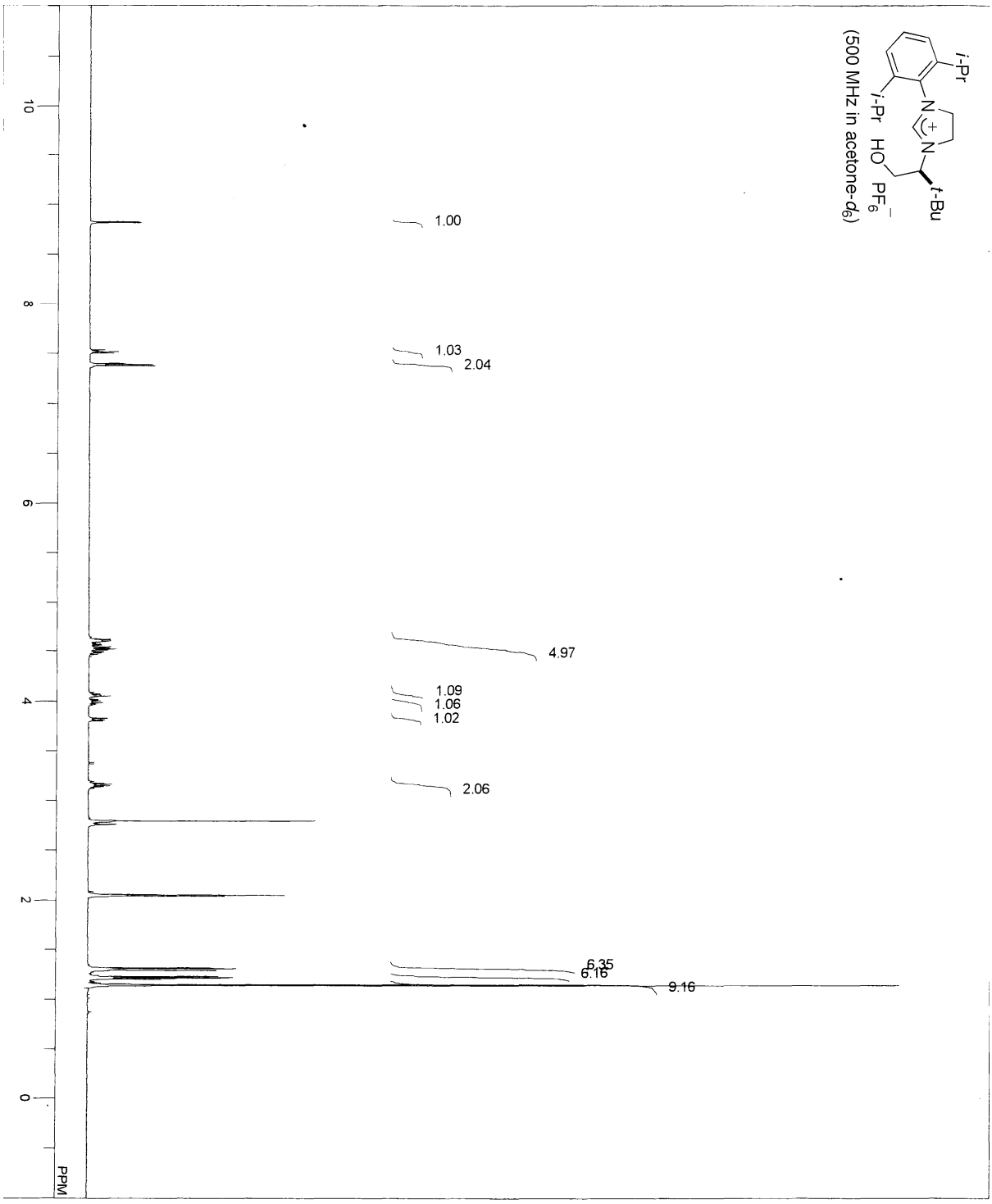

Me
Me
N
N
HO
PF6−
t-Bu
(125 MHz in acetone-d6)
161.1602
136.9317
134.4923
130.9487
129.9680
71.3993
57.9912
51.4726
49.9315
34.2407
30.3015
30.1449
29.9966
29.8400
29.6834
29.5351
29.3785
27.5490
17.6021
200
150
100
50
0
PPM

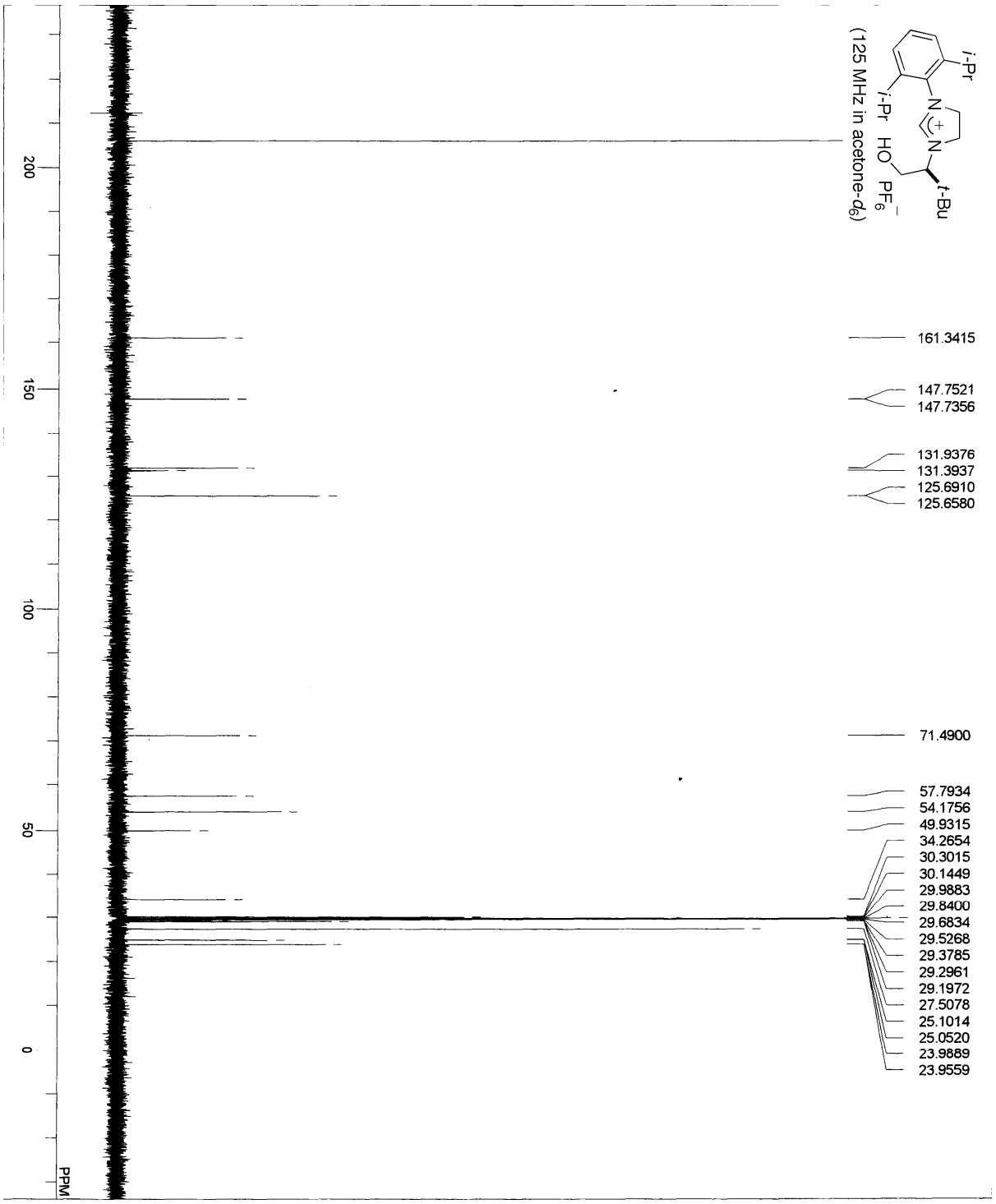

(500 MHz in acetone-d_6)
HO
PF_6^-
t-Bu
1.00
3.96
1.02
2.04
2.03
0.95
2.02
1.02
9.11
10
8
6
4
2
0
PPM

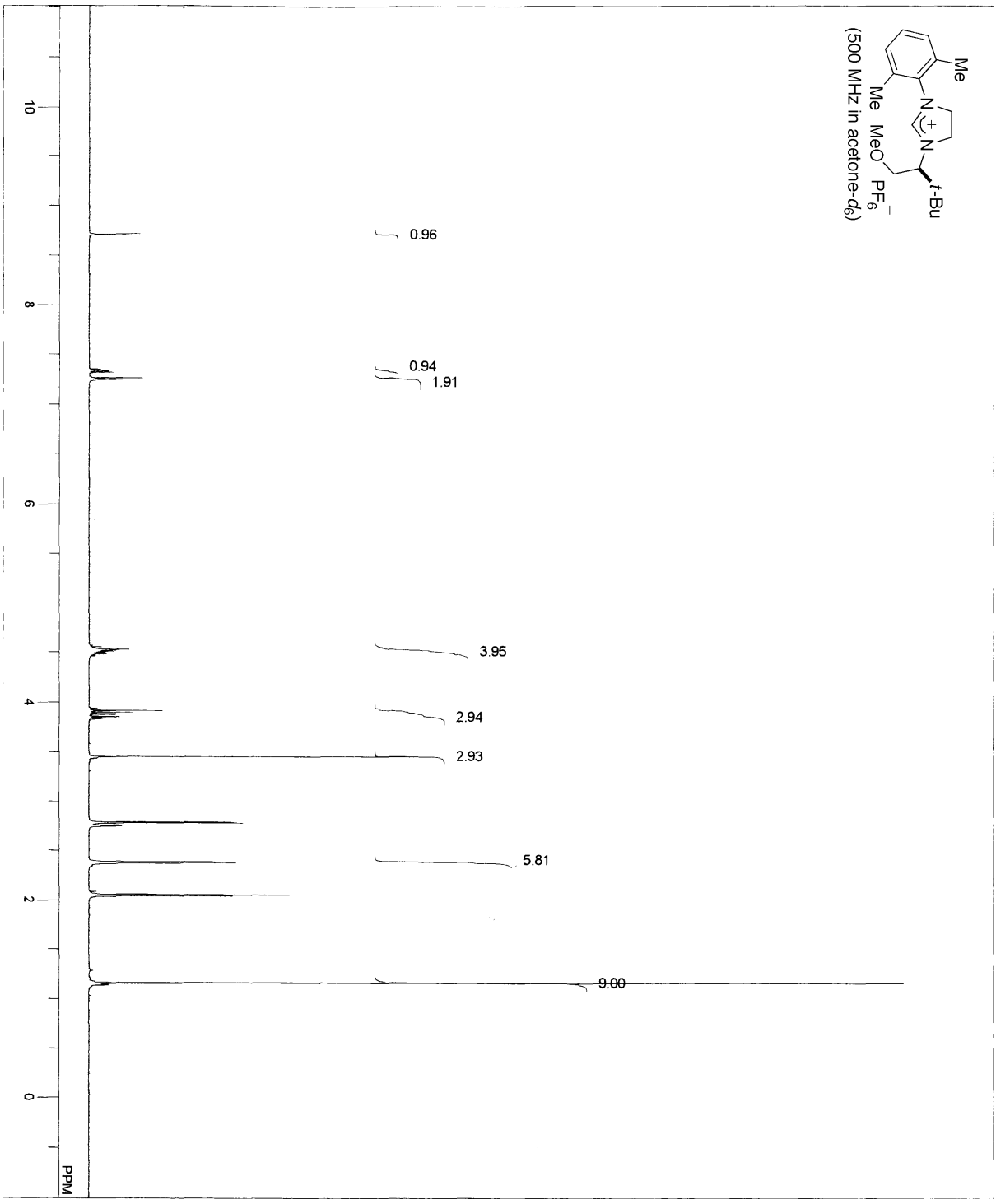

(125 MHz in acetone-d_6)
HO
PF_6^-
t-Bu
156.4711
137.3272
130.7592
127.6935
118.7933
72.1987
58.2797
49.7997
49.2970
34.3973
30.3015
30.1449
29.9883
29.8400
29.6834
29.5268
29.3785
27.5408
200
150
100
50
0
PPM

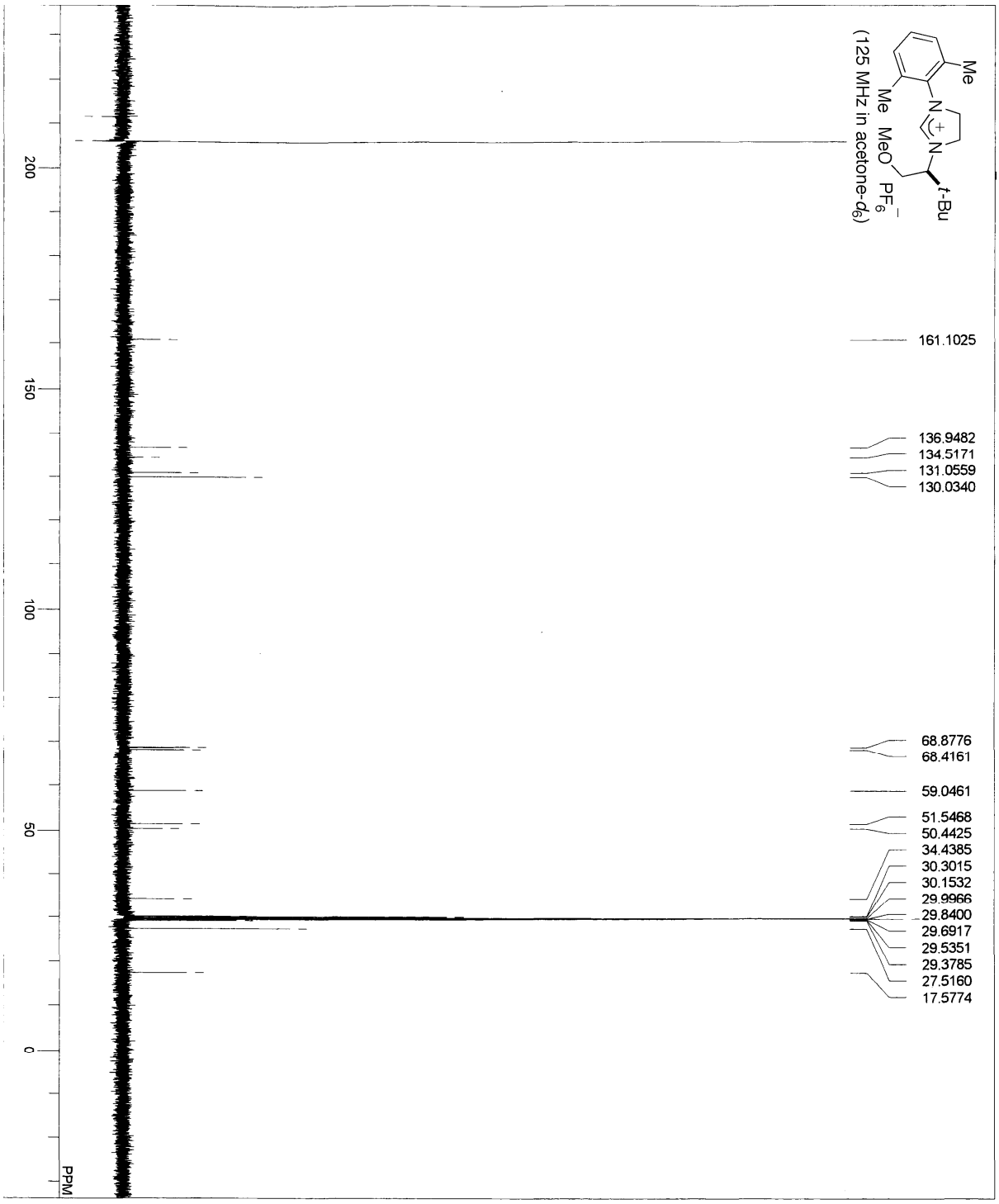

Et
Et
HO
PF6−
t-Bu
(500 MHz in acetone-d6)
1.00
0.97
2.09
5.07
1.04
1.09
0.99
6.32
6.47
9.42
10
8
6
4
2
0
PPM

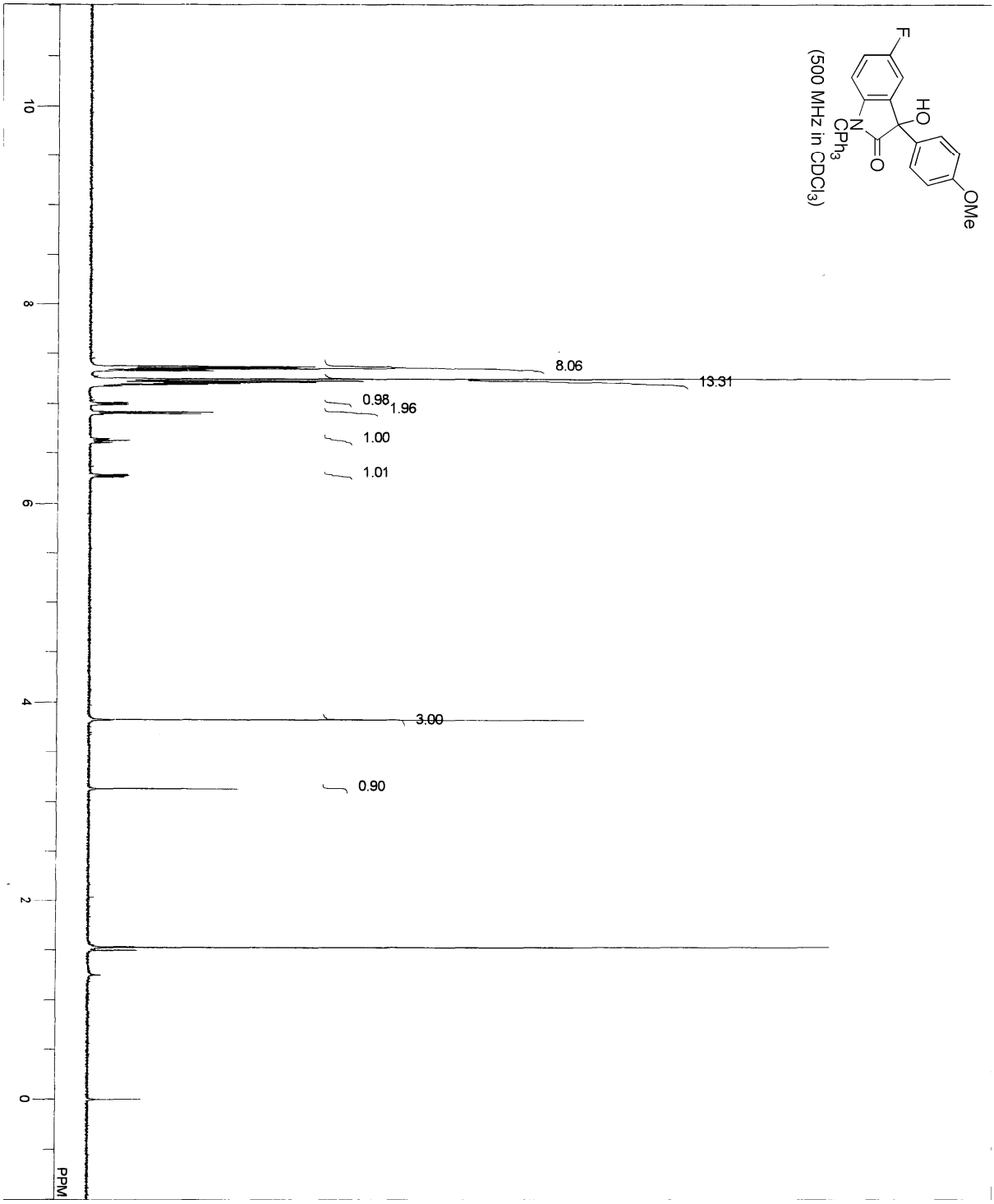

Et
Et
HO
PF6−
t-Bu
(125 MHz in acetone-d6)
161.3333
142.9394
142.9229
133.1243
131.5421
128.3034
128.2622
71.5147
57.9253
53.0219
50.0139
34.2901
30.3015
30.1532
29.9966
29.8400
29.6834
29.5351
29.3785
27.5490
24.5658
24.5410
15.5501
15.4842
200
150
100
50
0
PPM

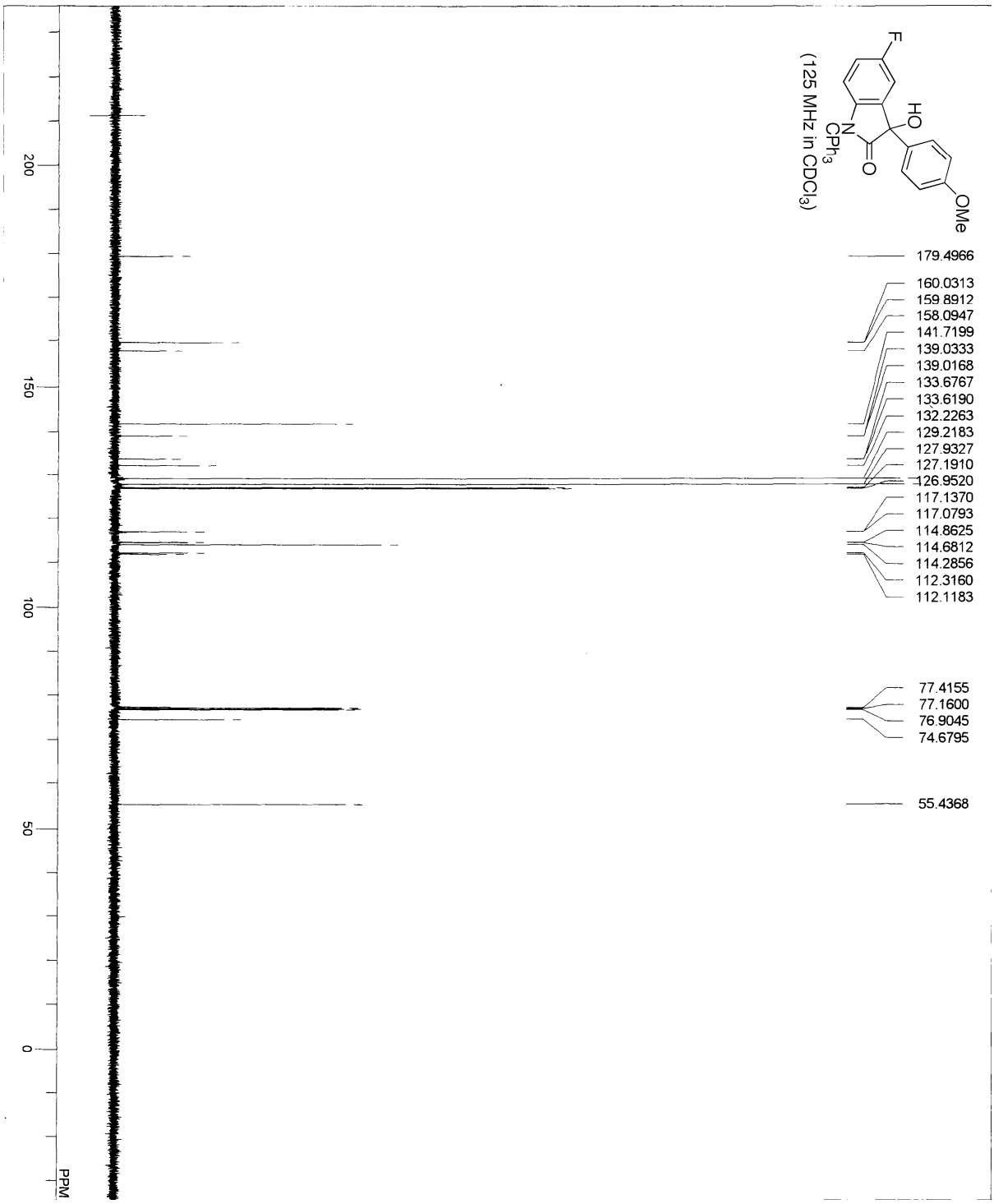

i-Pr
i-Pr
HO
t-Bu
PF6−
(500 MHz in acetone-d6)
1.00
1.03
2.04
4.97
1.09
1.06
1.02
2.06
6.35
6.16
9.16
10
8
6
4
2
0
PPM

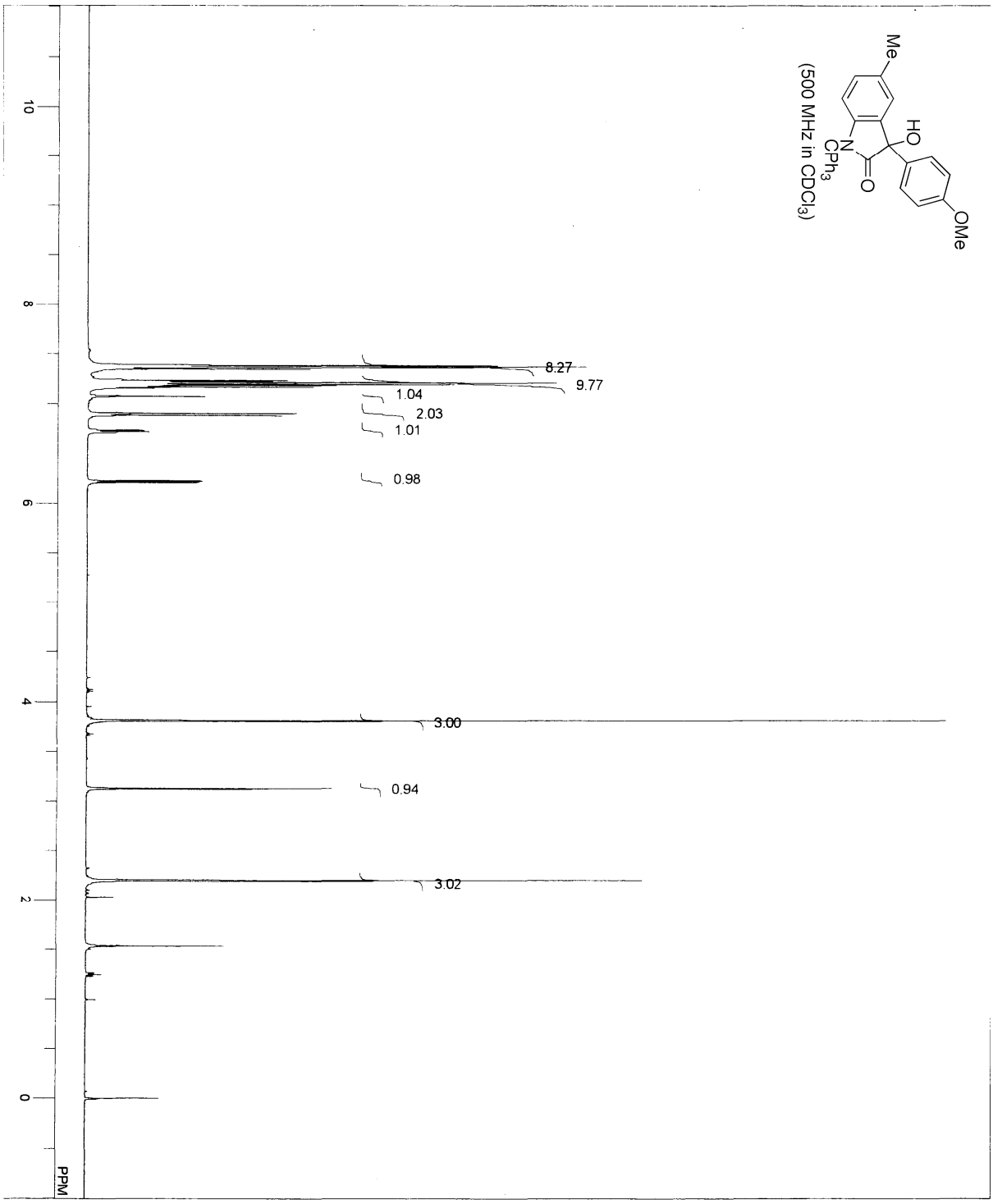

i-Pr
i-Pr
HO
PF6−
t-Bu
(125 MHz in acetone-d6)
161.3415
147.7521
147.7356
131.9376
131.3937
125.6910
125.6580
71.4900
57.7934
54.1756
49.9315
34.2654
30.3015
30.1449
29.9883
29.8400
29.6834
29.5268
29.3785
29.2961
29.1972
27.5078
25.1014
25.0520
23.9889
23.9559
200
150
100
50
0
PPM

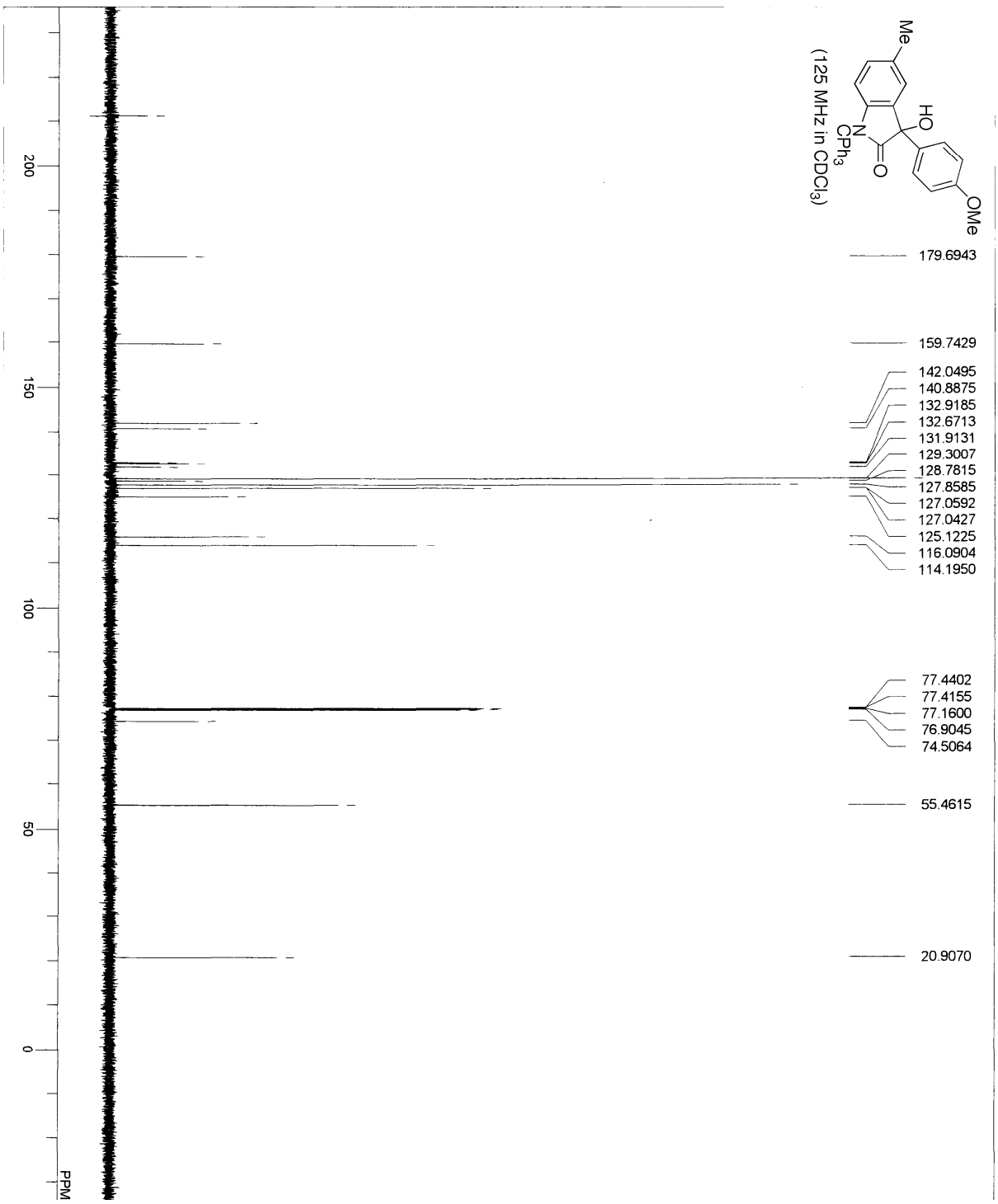

Me
Me MeO
t-Bu
PF6−
(500 MHz in acetone-d6)
0.96
0.94
1.91
3.95
2.94
2.93
5.81
9.00
10
8
6
4
2
0
PPM

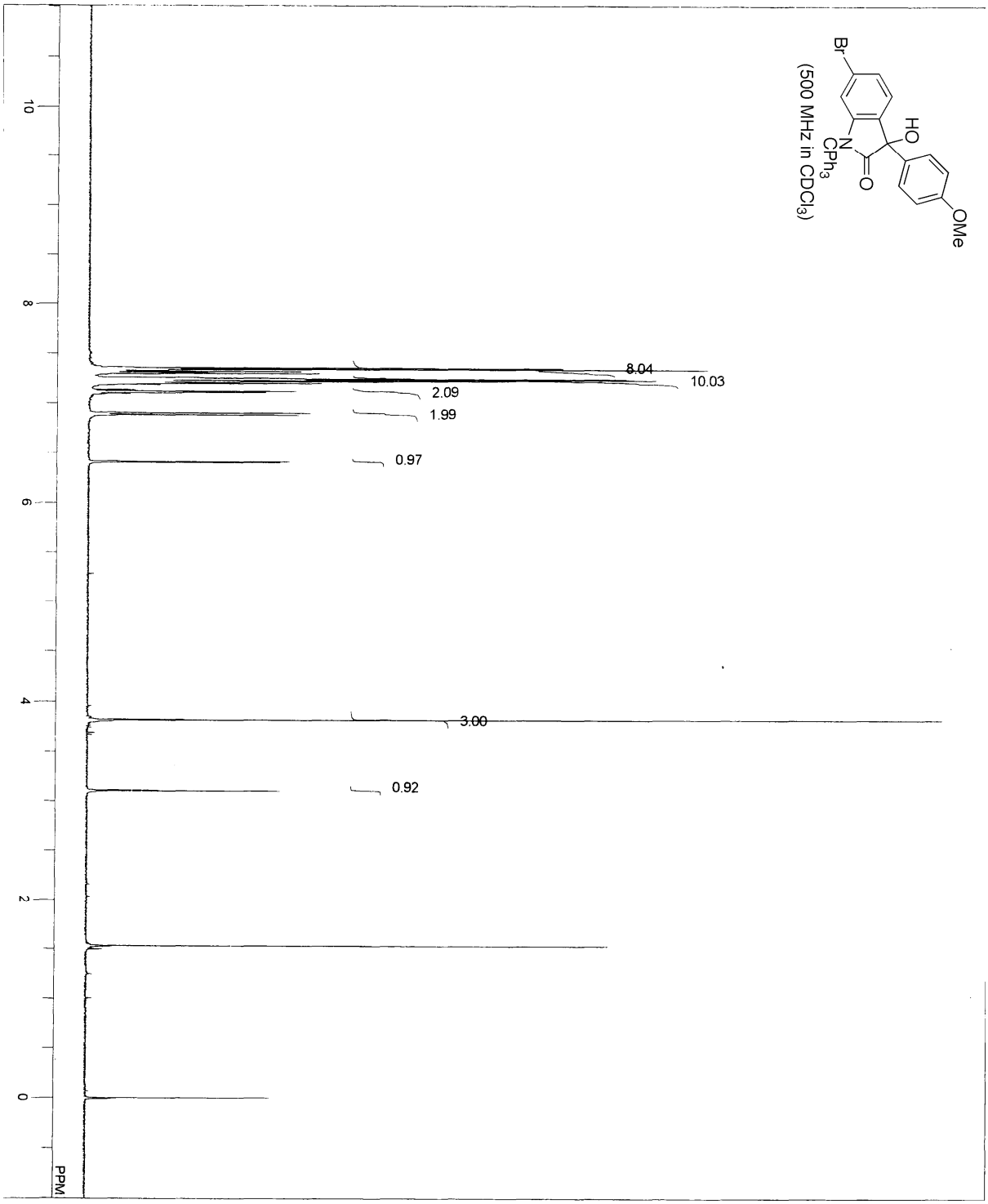

Me
Me
MeO
PF6−
t-Bu
(125 MHz in acetone-d6)
161.1025
136.9482
134.5171
131.0559
130.0340
68.8776
68.4161
59.0461
51.5468
50.4425
34.4385
30.3015
30.1532
29.9966
29.8400
29.6917
29.5351
29.3785
27.5160
17.5774
200
150
100
50
0
PPM

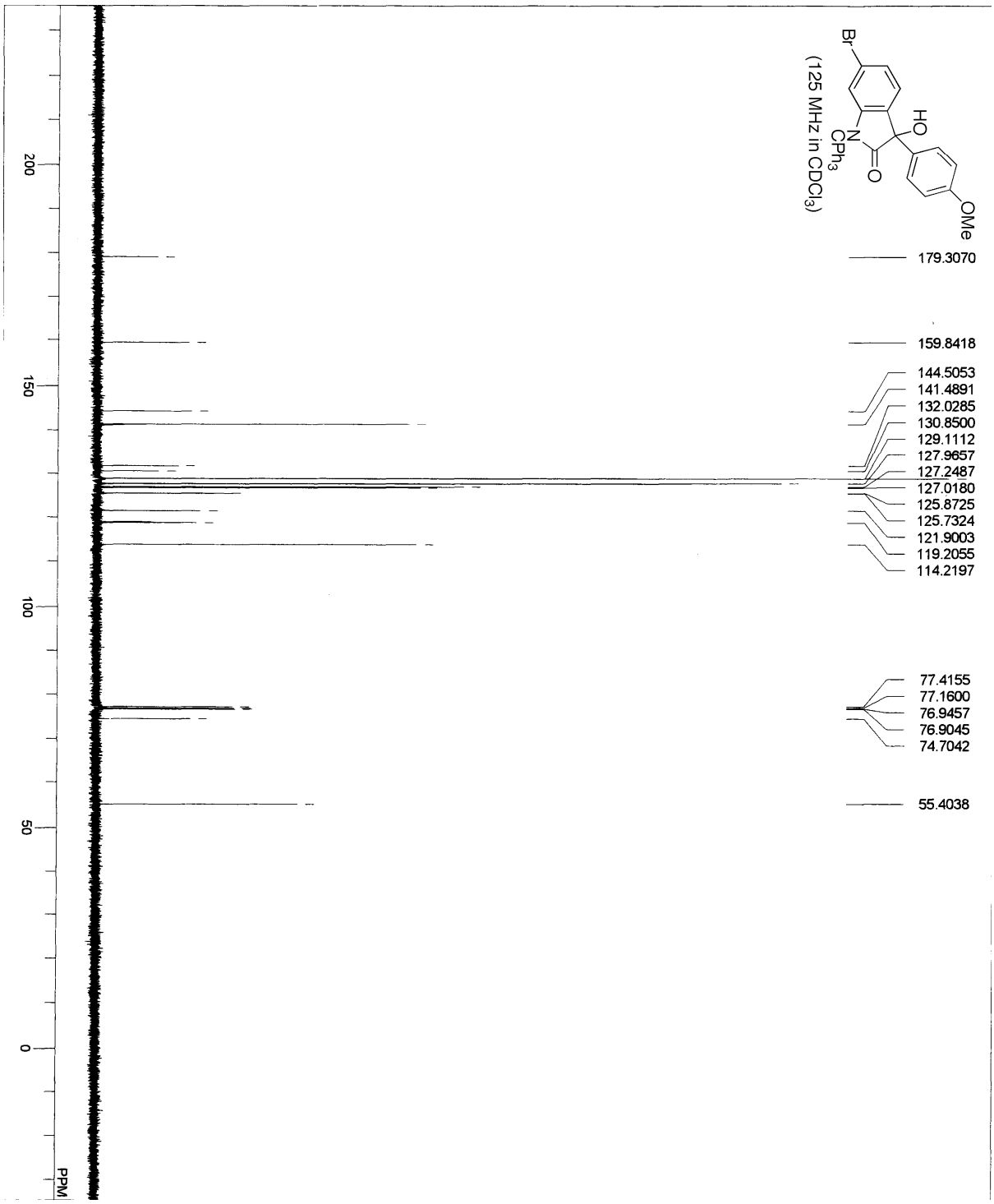

F
HO
N
CPh3
O
OMe
(500 MHz in CDCl3)
8.06
13.31
0.98
1.96
1.00
1.01
3.00
0.90
10
8
6
4
2
0
PPM

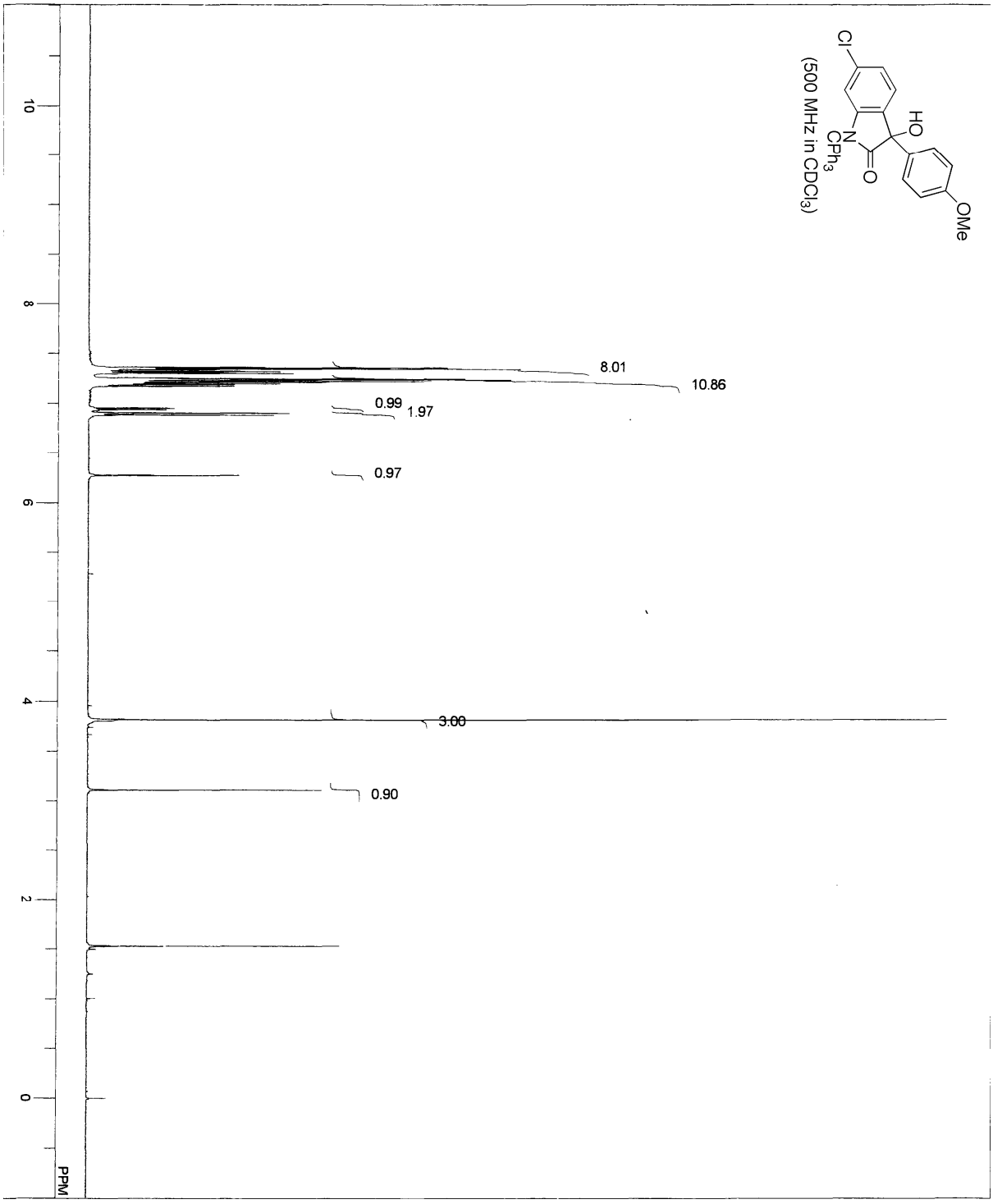

(125 MHz in CDCl3)
F
HO
N
CPh3
O
OMe
179.4966
160.0313
159.8912
158.0947
141.7199
139.0333
139.0168
133.6767
133.6190
132.2263
129.2183
127.9327
127.1910
126.9520
117.1370
117.0793
114.8625
114.6812
114.2856
112.3160
112.1183
77.4155
77.1600
76.9045
74.6795
55.4368
200
150
100
50
0
PPM

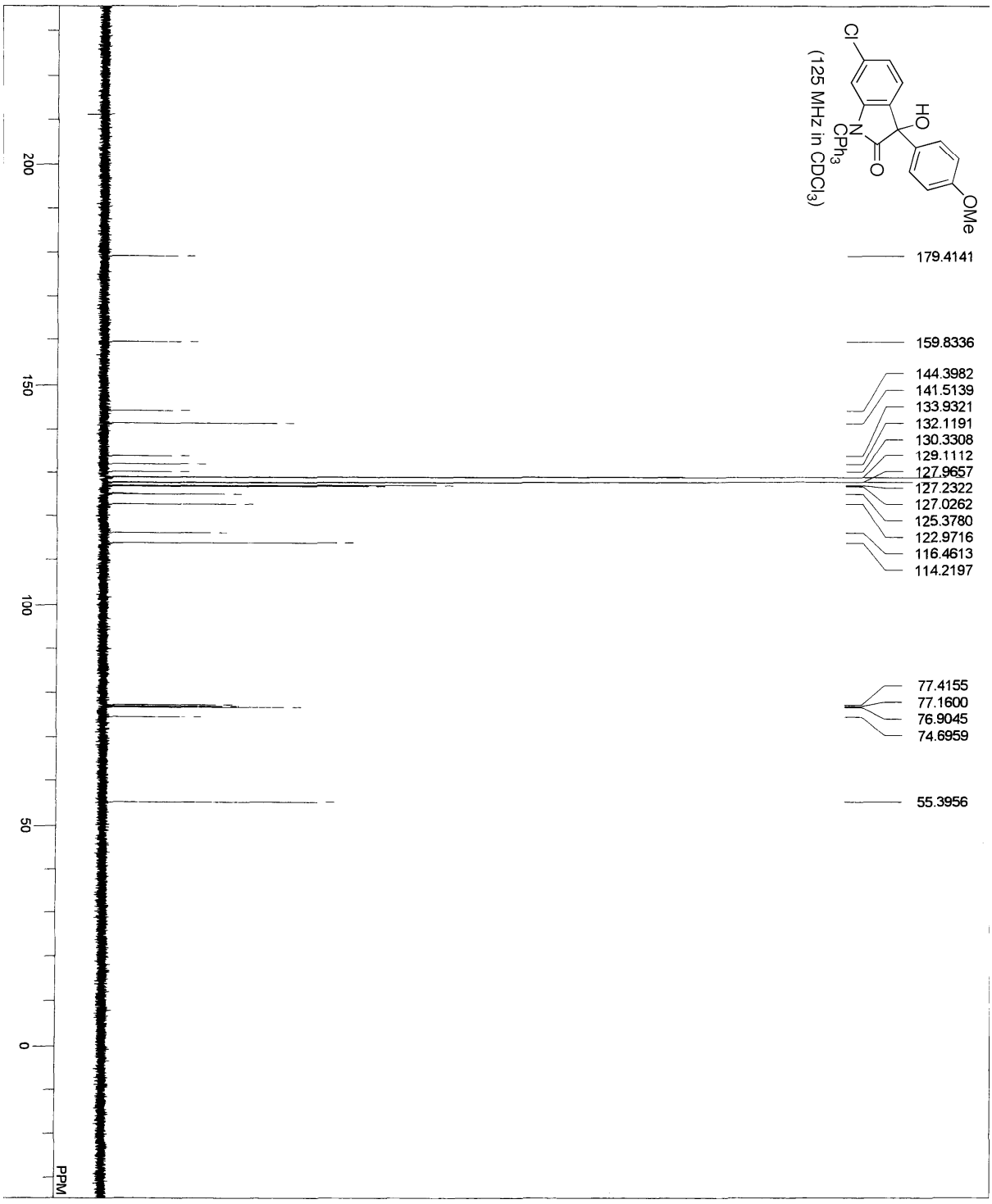

Me
HO
N
CPh3
O
OMe
(500 MHz in CDCl3)
8.27
9.77
1.04
2.03
1.01
0.98
3.00
0.94
3.02
10
8
6
4
2
0
PPM

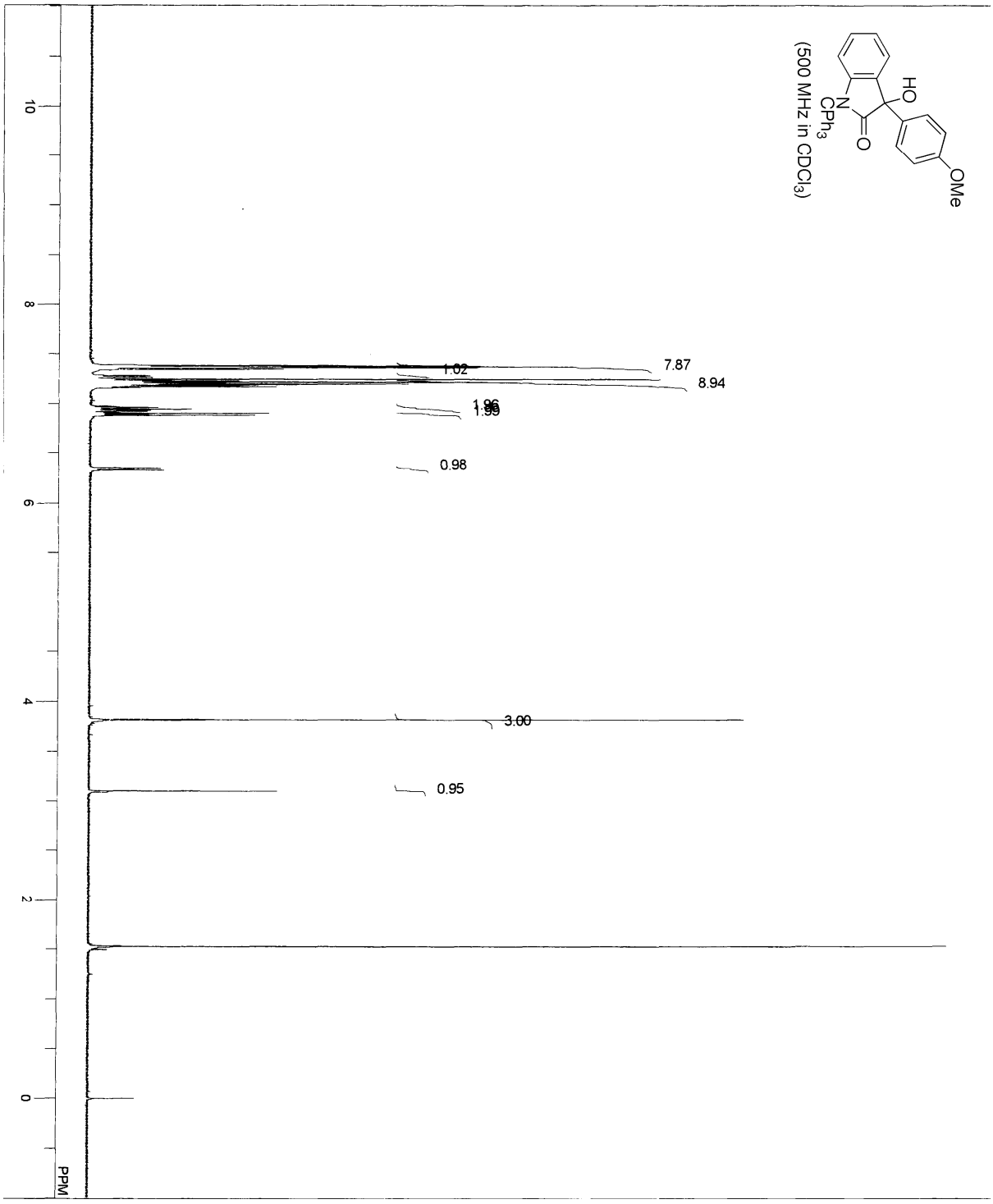

(125 MHz in CDCl3)
Me
HO
N
CPh3
O
OMe
179.6943
159.7429
142.0495
140.8875
132.9185
132.6713
131.9131
129.3007
128.7815
127.8585
127.0592
127.0427
125.1225
116.0904
114.1950
77.4402
77.4155
77.1600
76.9045
74.5064
55.4615
20.9070
200
150
100
50
0
PPM

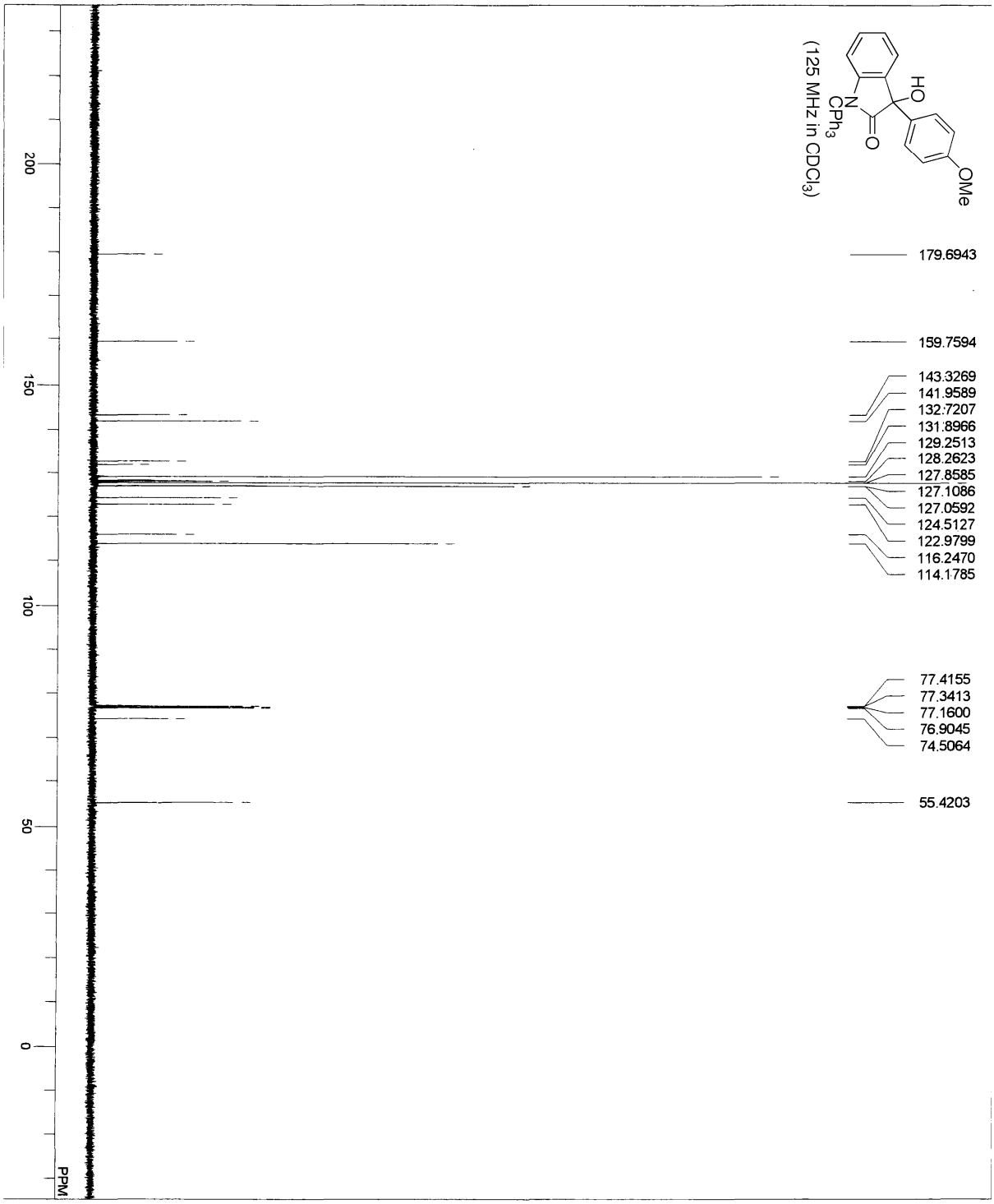

Br
HO
N
CPh3
O
OMe
(500 MHz in CDCl3)
8.04
10.03
2.09
1.99
0.97
3.00
0.92
10
8
6
4
2
0
PPM

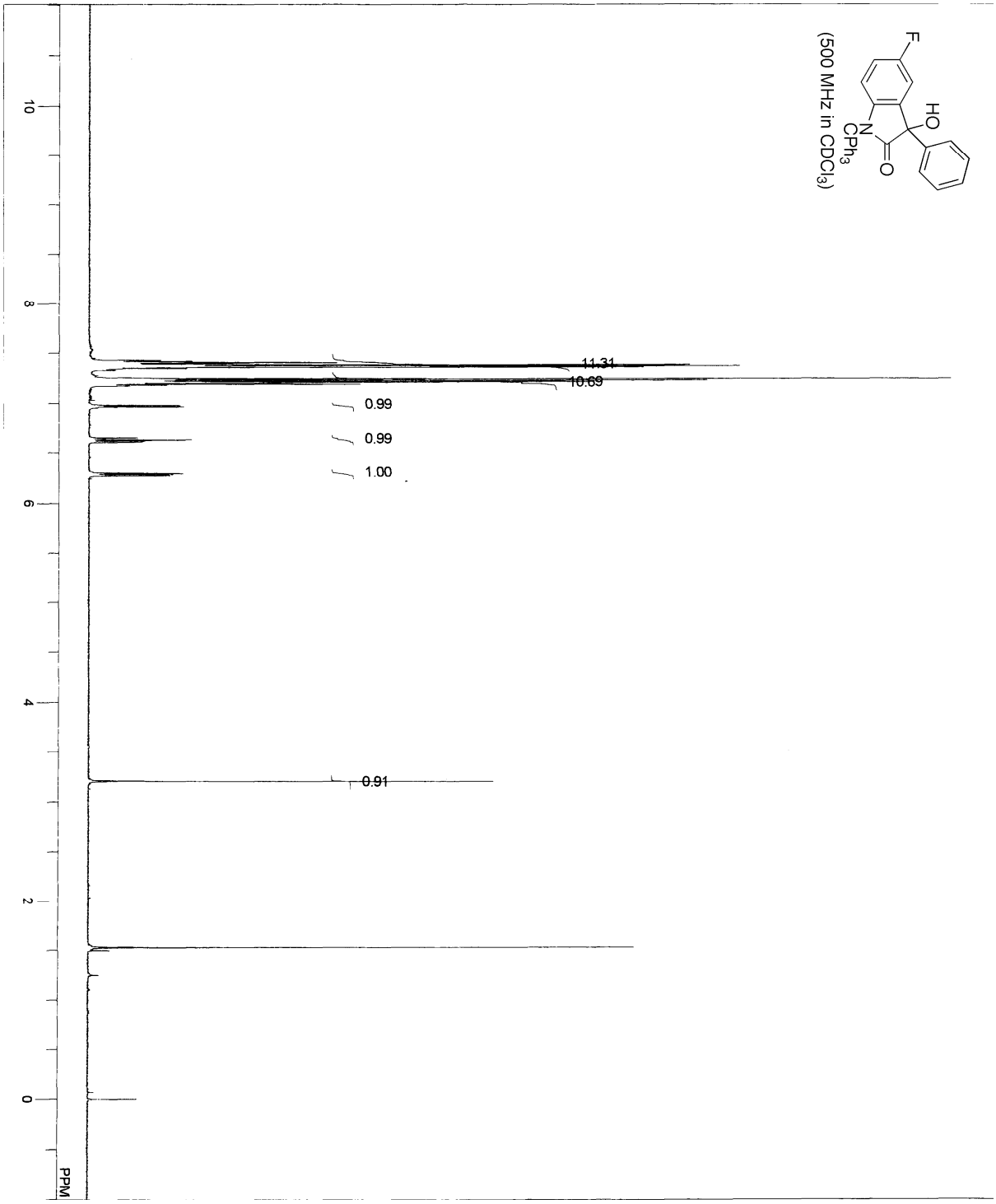

(125 MHz in CDCl3)
Br
N
CPh3
O
HO
OMe
179.3070
159.8418
144.5053
141.4891
132.0285
130.8500
129.1112
127.9657
127.2487
127.0180
125.8725
125.7324
121.9003
119.2055
114.2197
77.4155
77.1600
76.9457
76.9045
74.7042
55.4038
200
150
100
50
0
PPM

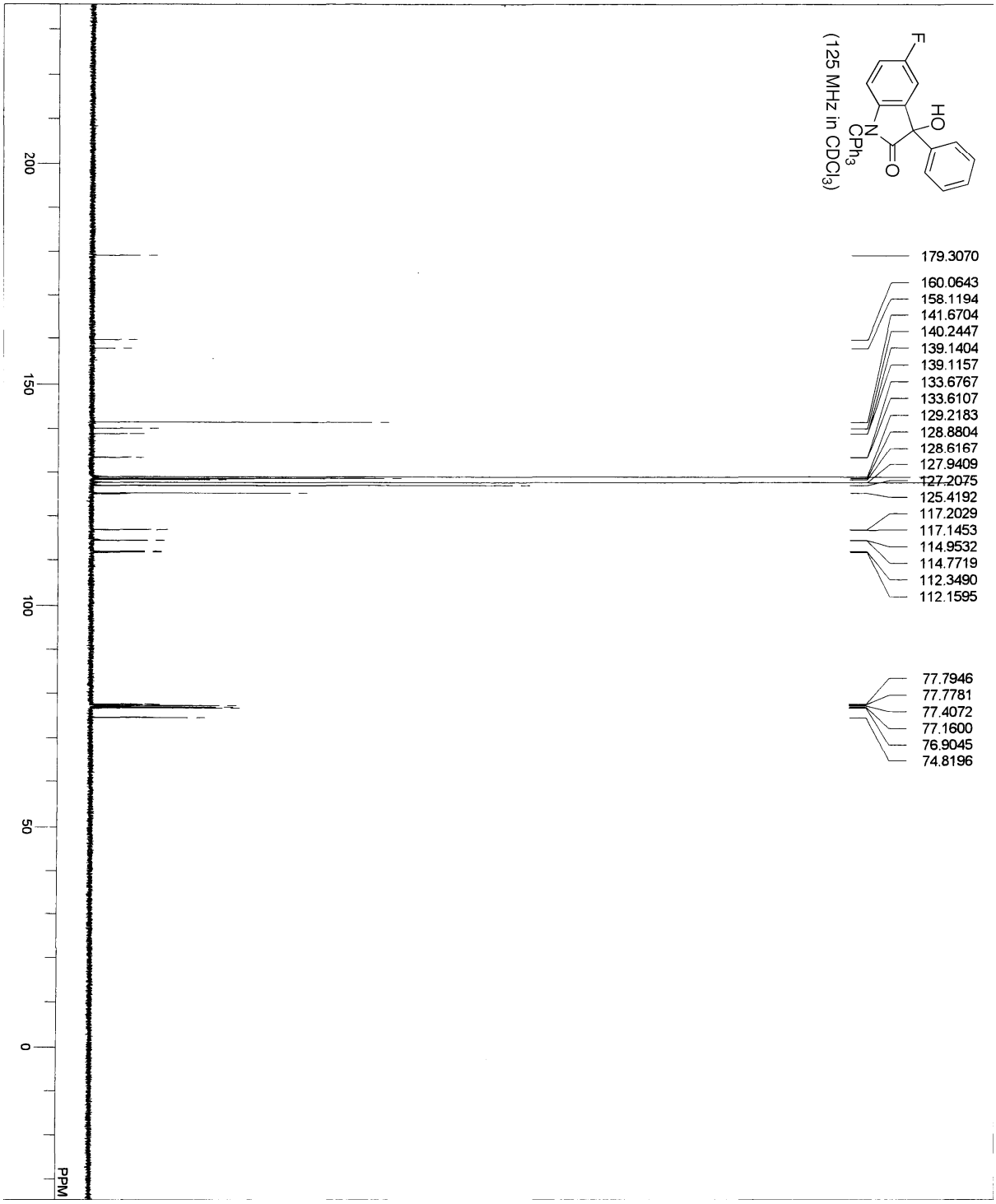

Cl
HO
N
CPh3
O
OMe
(500 MHz in CDCl3)
8.01
10.86
0.99
1.97
0.97
3.00
0.90
10
8
6
4
2
0
PPM

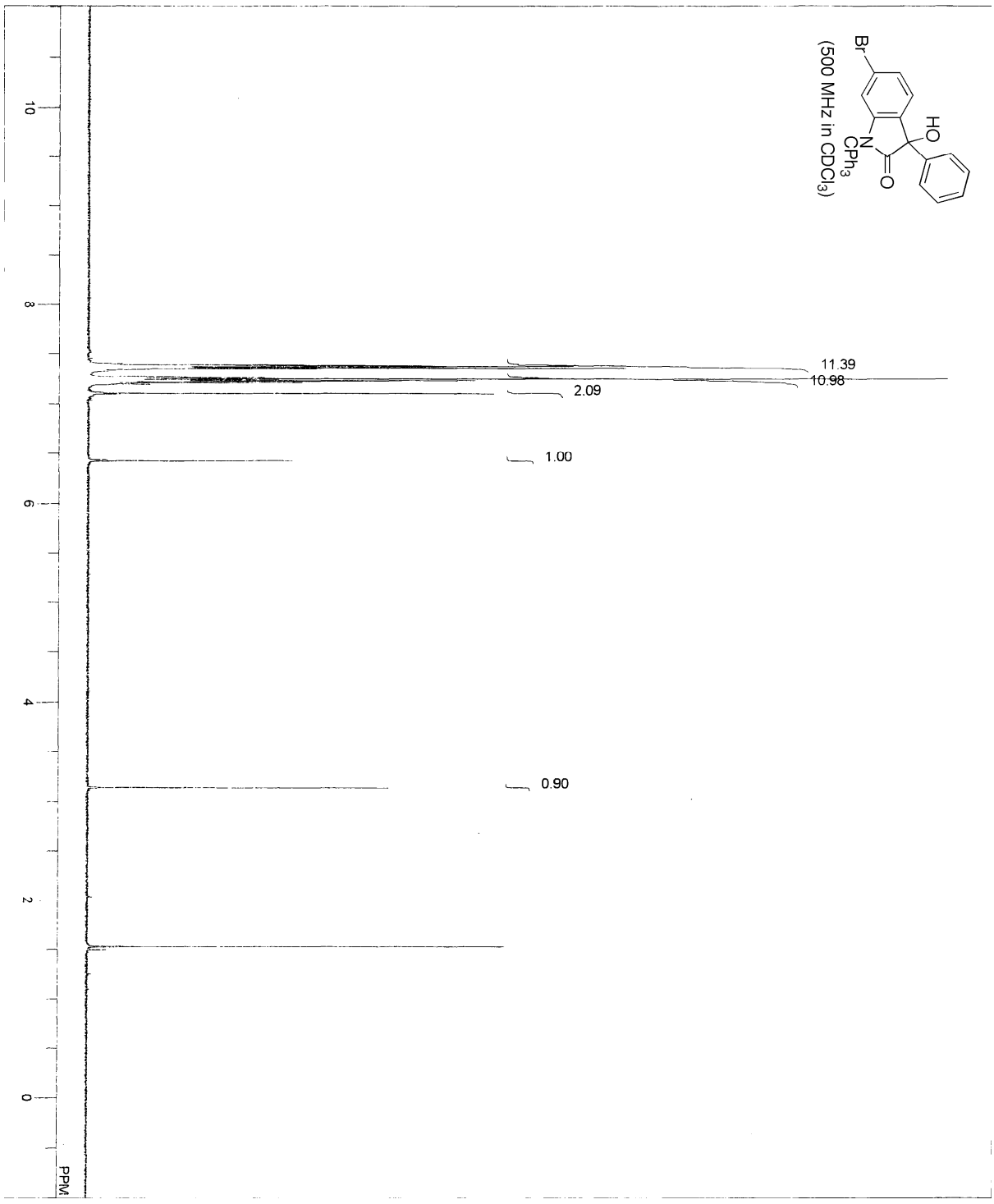

(125 MHz in CDCl3)
Cl
HO
N
CPh3
O
OMe
179.4141
159.8336
144.3982
141.5139
133.9321
132.1191
130.3308
129.1112
127.9657
127.2322
127.0262
125.3780
122.9716
116.4613
114.2197
77.4155
77.1600
76.9045
74.6959
55.3956
200
150
100
50
0
PPM

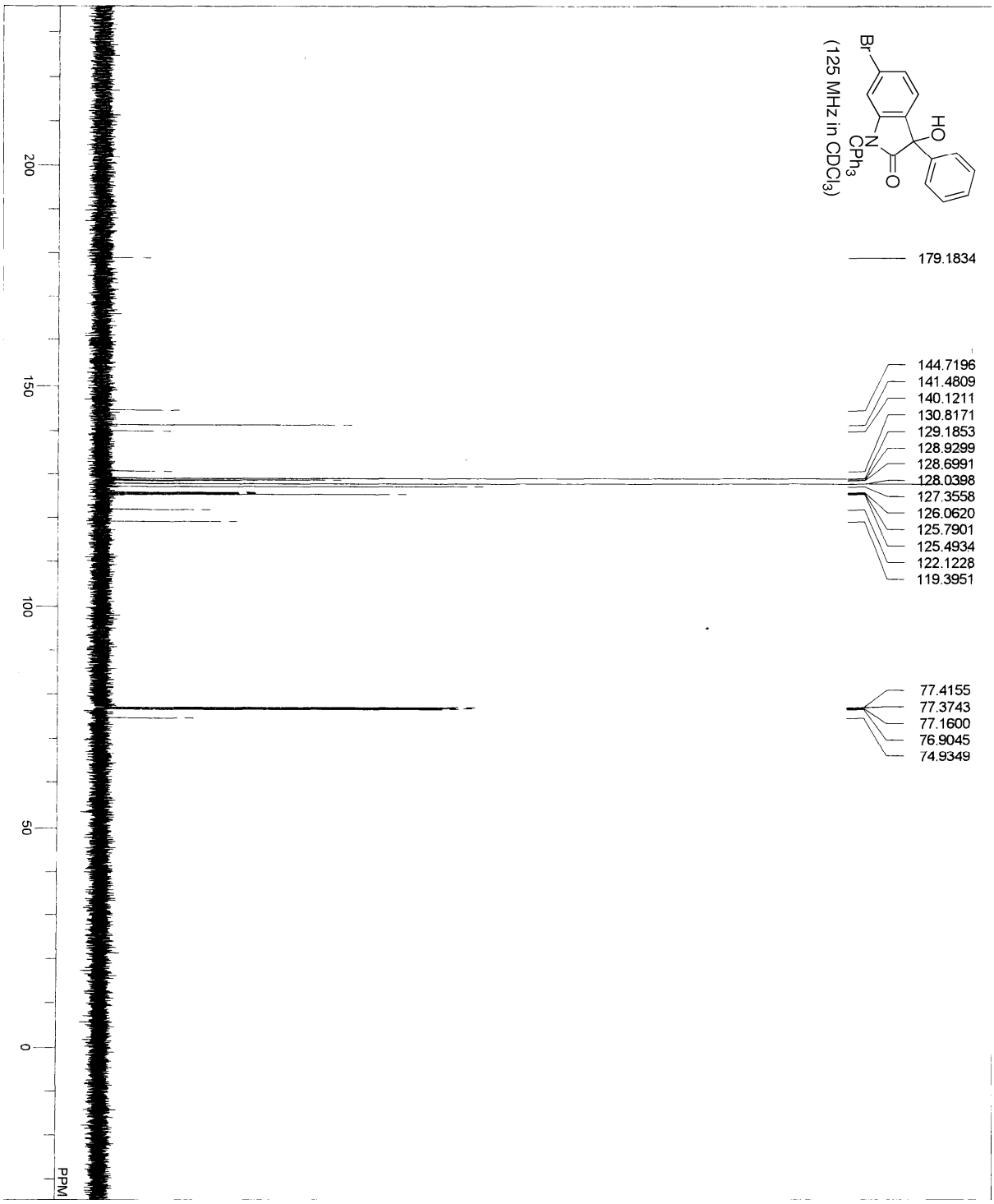

(500 MHz in CDCl3)
HO
N
CPh3
O
OMe
7.87
1.02
8.94
1.96
1.99
0.98
3.00
0.95
PPM

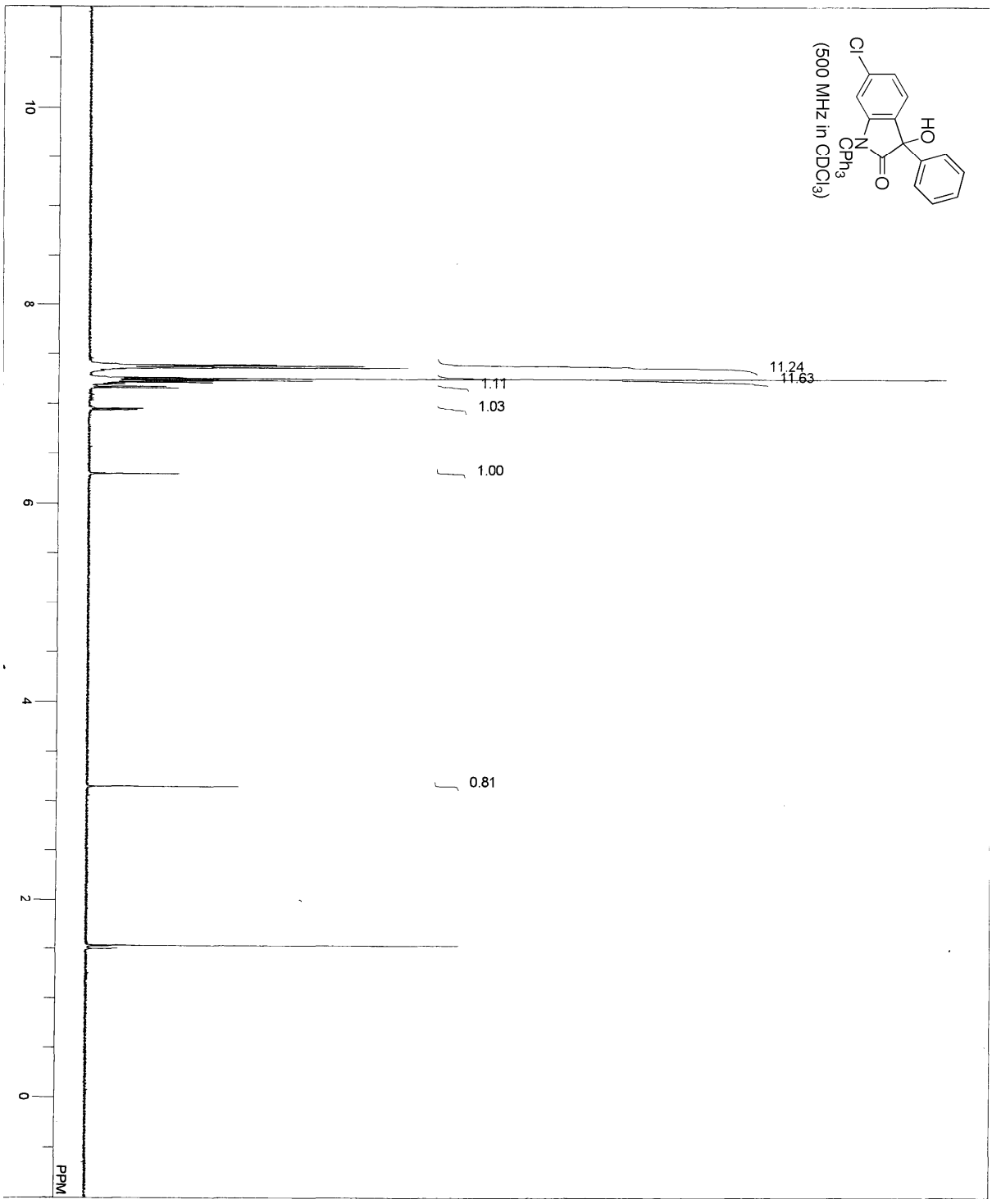

(125 MHz in CDCl3)
N
CPh3
O
HO
OMe
179.6943
159.7594
143.3269
141.9589
132.7207
131.8966
129.2513
128.2623
127.8585
127.1086
127.0592
124.5127
122.9799
116.2470
114.1785
77.4155
77.3413
77.1600
76.9045
74.5064
55.4203
200
150
100
50
0
PPM

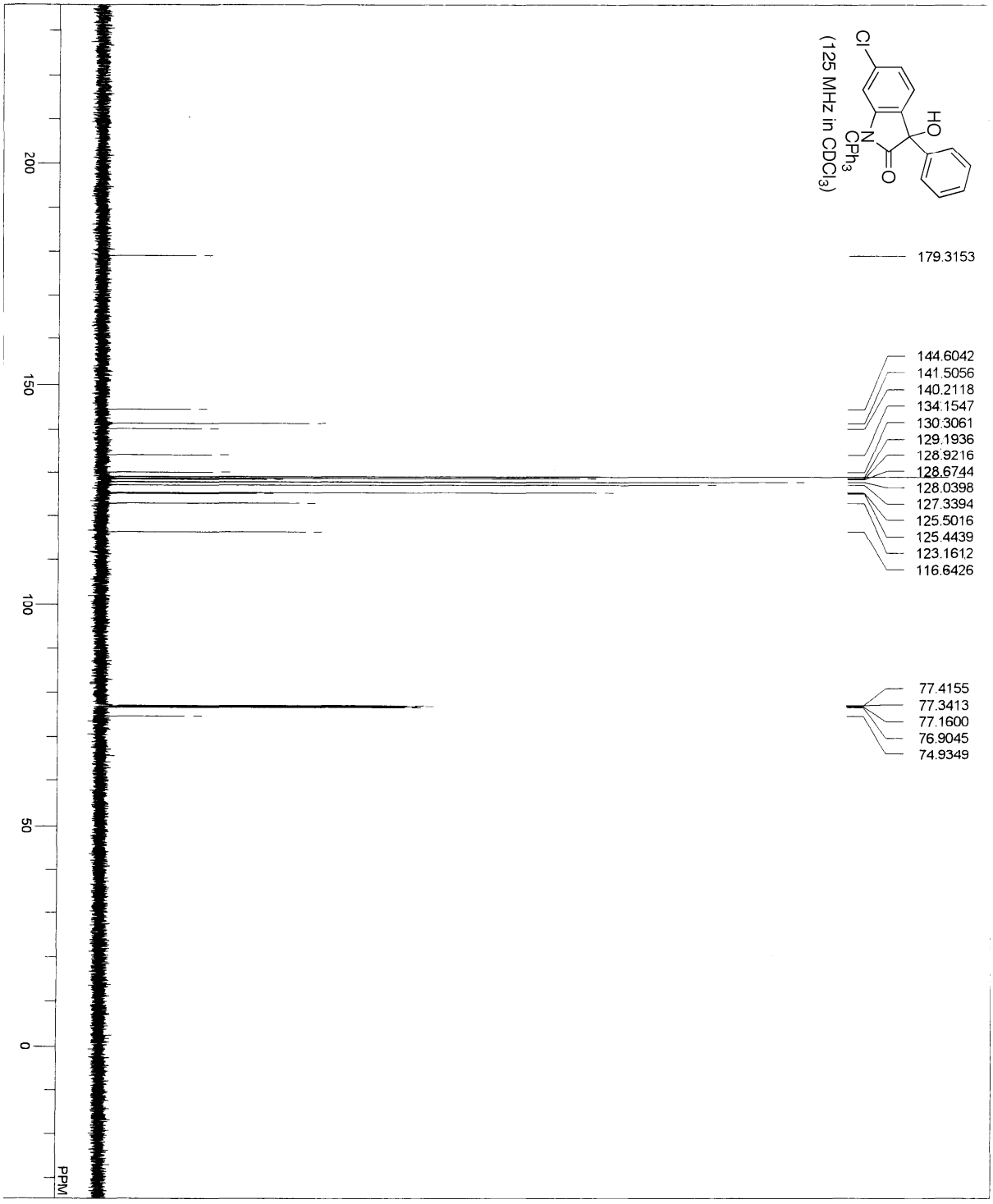

F
HO
N
CPh3
O
(500 MHz in CDCl3)
11.31
10.69
0.99
0.99
1.00
0.91
10
8
6
4
2
0
PPM

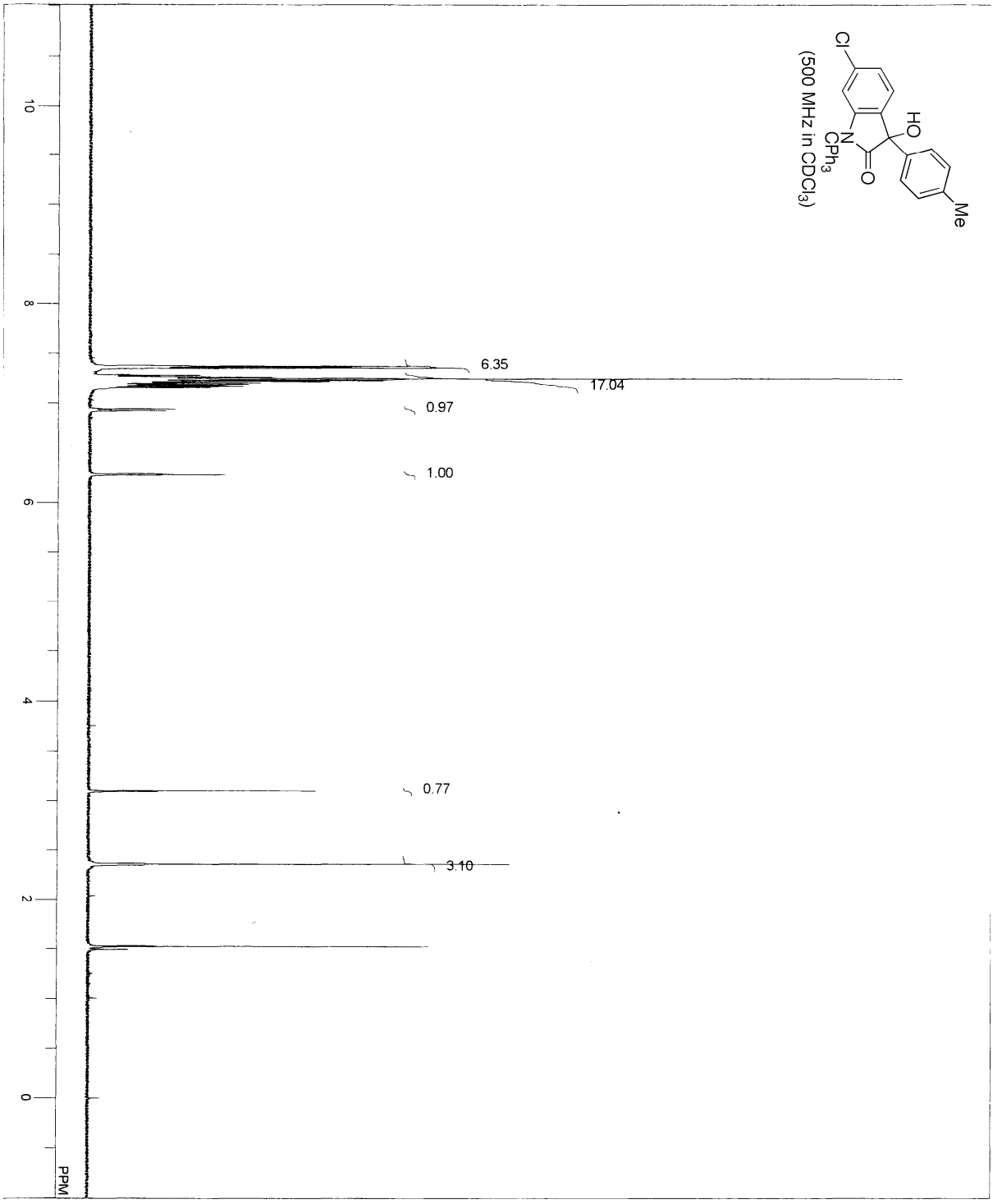

(125 MHz in CDCl3)
F
HO
N
CPh3
O
179.3070
160.0643
158.1194
141.6704
140.2447
139.1404
139.1157
133.6767
133.6107
129.2183
128.8804
128.6167
127.9409
127.2075
125.4192
117.2029
117.1453
114.9532
114.7719
112.3490
112.1595
77.7946
77.7781
77.4072
77.1600
76.9045
74.8196
200
150
100
50
0
PPM

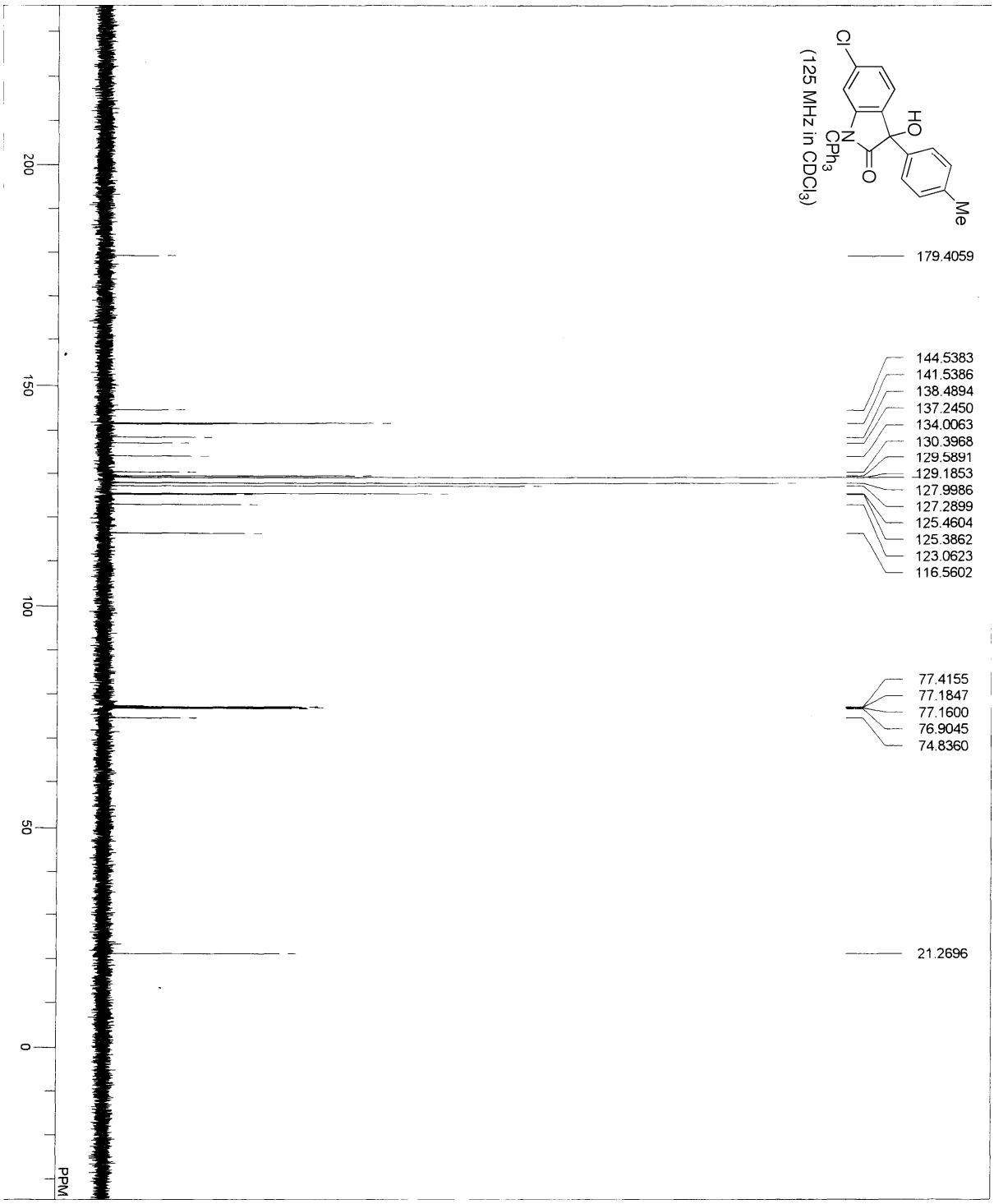

(500 MHz in $CDCl_3$)
Br
HO
N
CPh_3
O
11.39
10.98
2.09
1.00
0.90
10
8
6
4
2
0
PPM

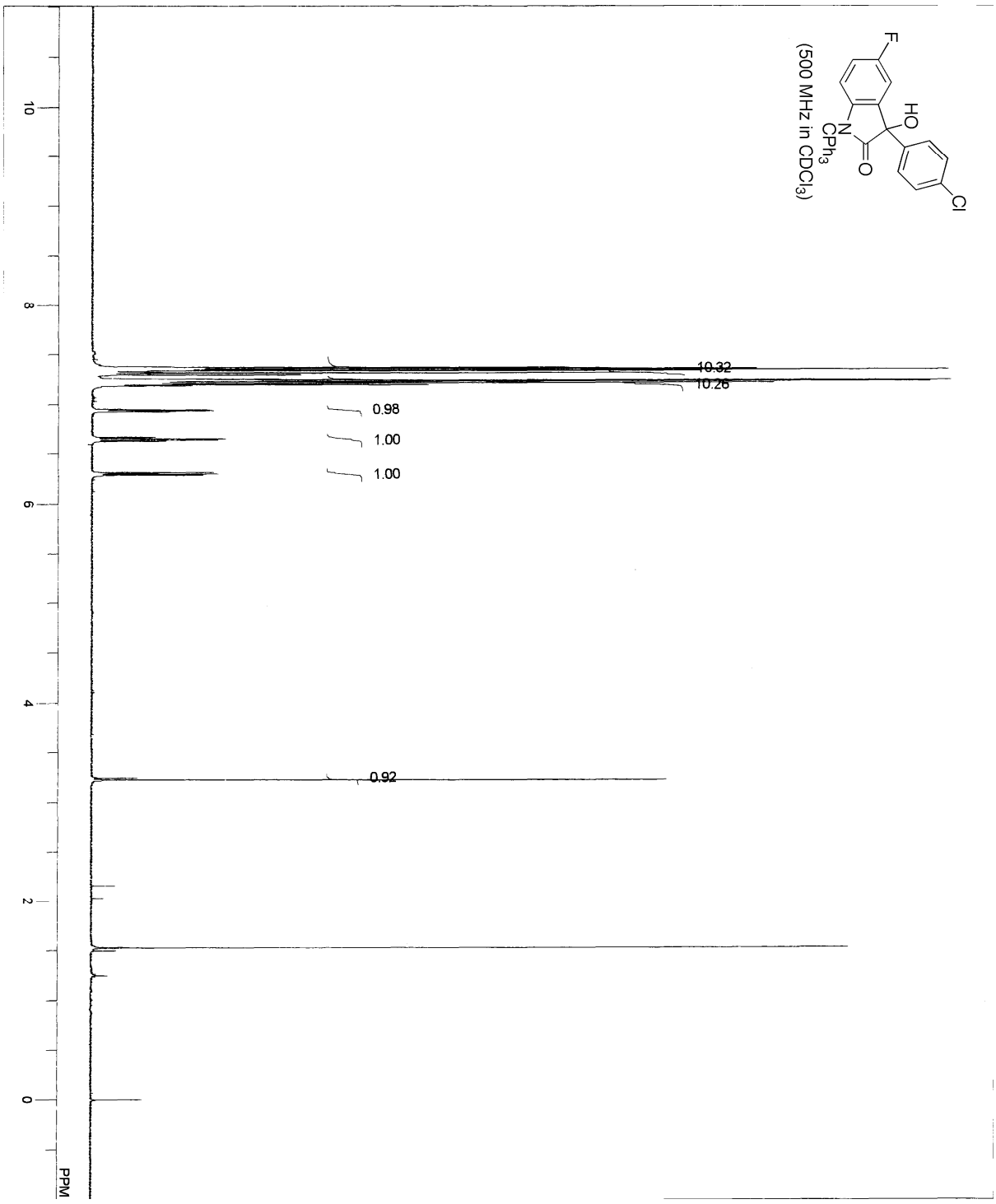

(125 MHz in CDCl3)
Br
HO
N
CPh3
O
179.1834
144.7196
141.4809
140.1211
130.8171
129.1853
128.9299
128.6991
128.0398
127.3558
126.0620
125.7901
125.4934
122.1228
119.3951
77.4155
77.3743
77.1600
76.9045
74.9349
200
150
100
50
0
PPM

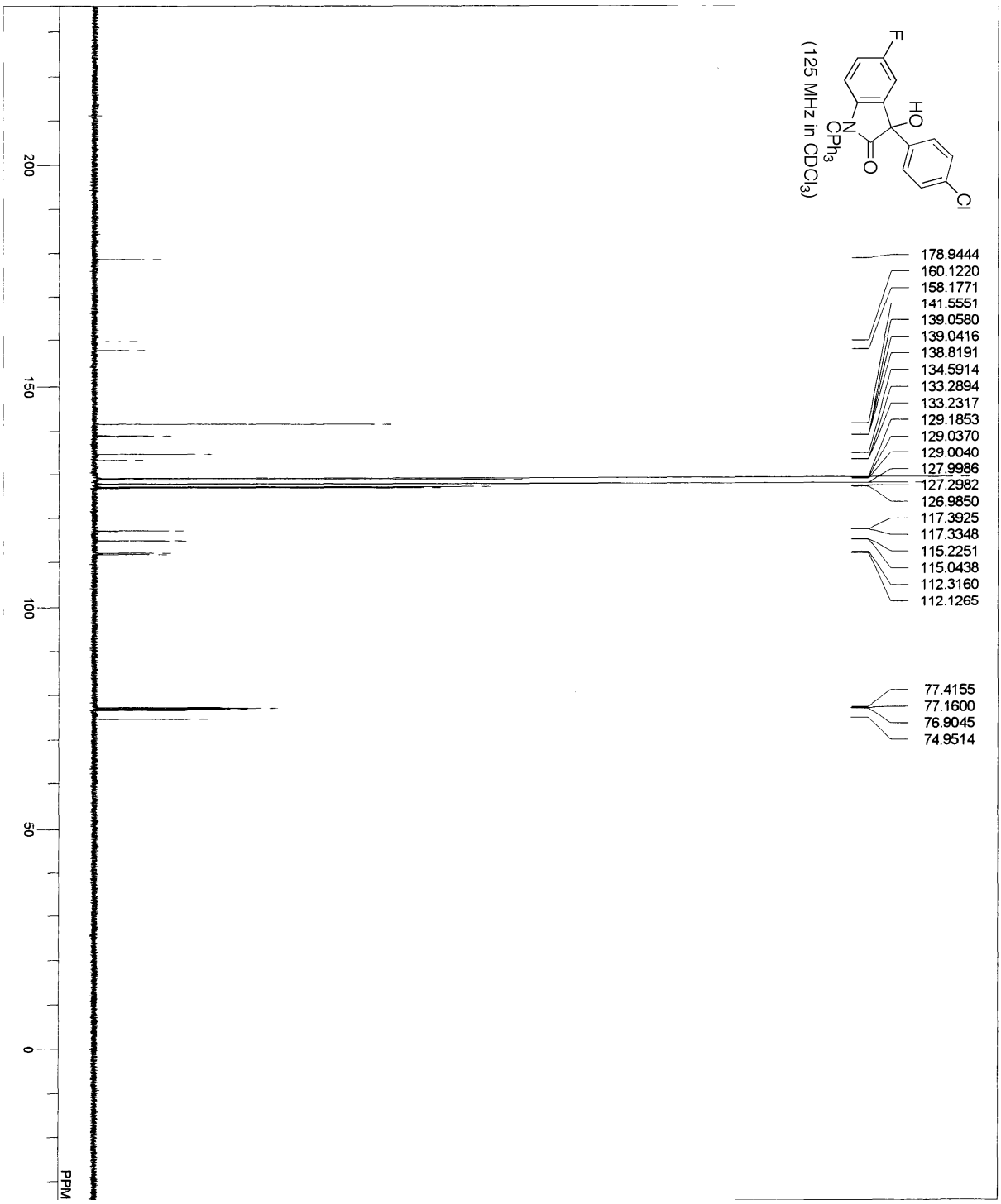

(500 MHz in CDCl3)
Cl
HO
N
CPh3
O
11.24
11.63
1.11
1.03
1.00
0.81
10
8
6
4
2
0
PPM

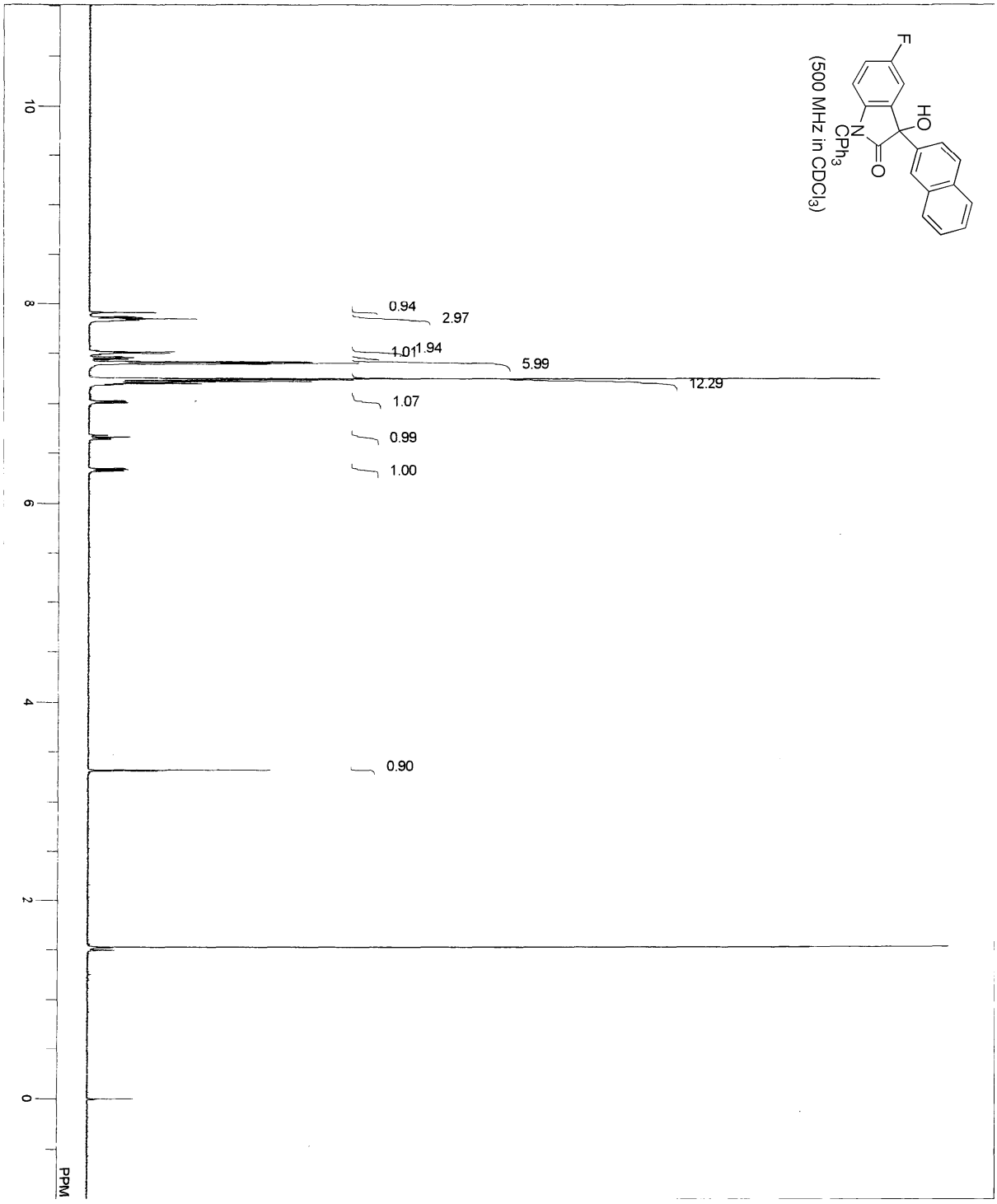

(125 MHz in CDCl3)
Cl
HO
N
CPh3
O
179.3153
144.6042
141.5056
140.2118
134.1547
130.3061
129.1936
128.9216
128.6744
128.0398
127.3394
125.5016
125.4439
123.1612
116.6426
77.4155
77.3413
77.1600
76.9045
74.9349
200
150
100
50
0
PPM

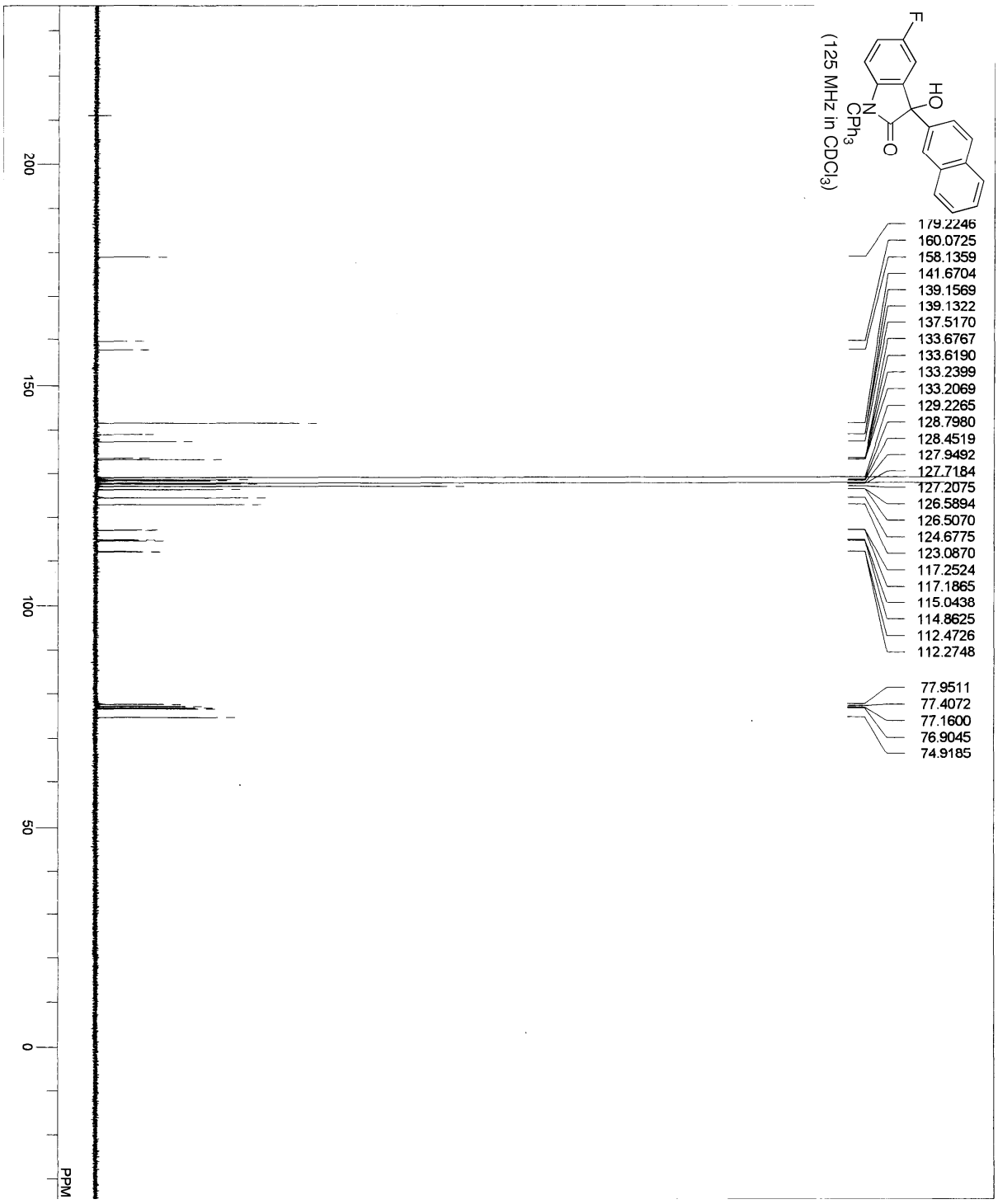

Cl
HO
N
CPh3
O
Me
(500 MHz in CDCl3)
6.35
17.04
0.97
1.00
0.77
3.10
10
8
6
4
2
0
PPM

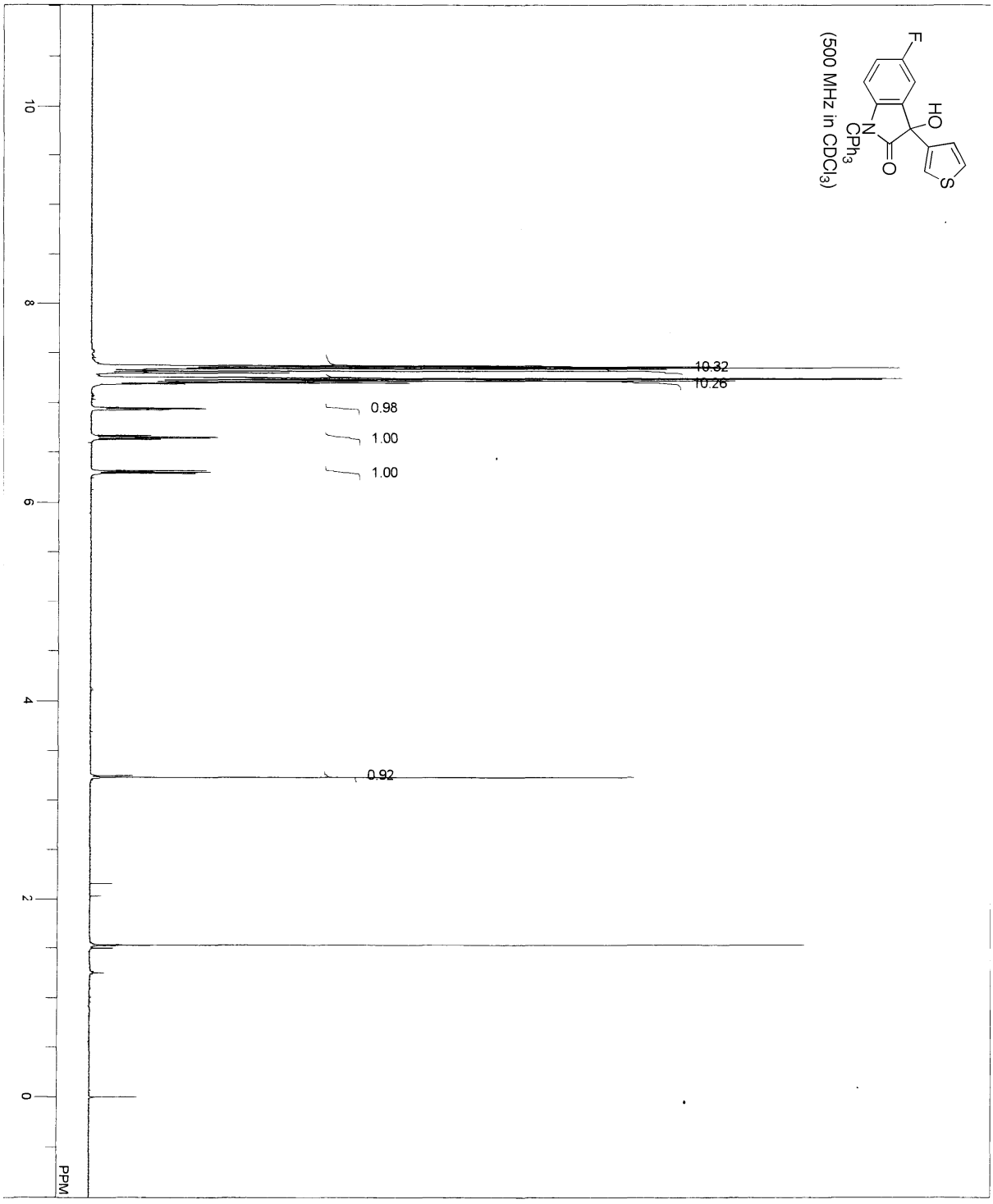

(125 MHz in CDCl3)
Cl
HO
N
CPh3
O
Me
179.4059
144.5383
141.5386
138.4894
137.2450
134.0063
130.3968
129.5891
129.1853
127.9986
127.2899
125.4604
125.3862
123.0623
116.5602
77.4155
77.1847
77.1600
76.9045
74.8360
21.2696
200
150
100
50
0
PPM

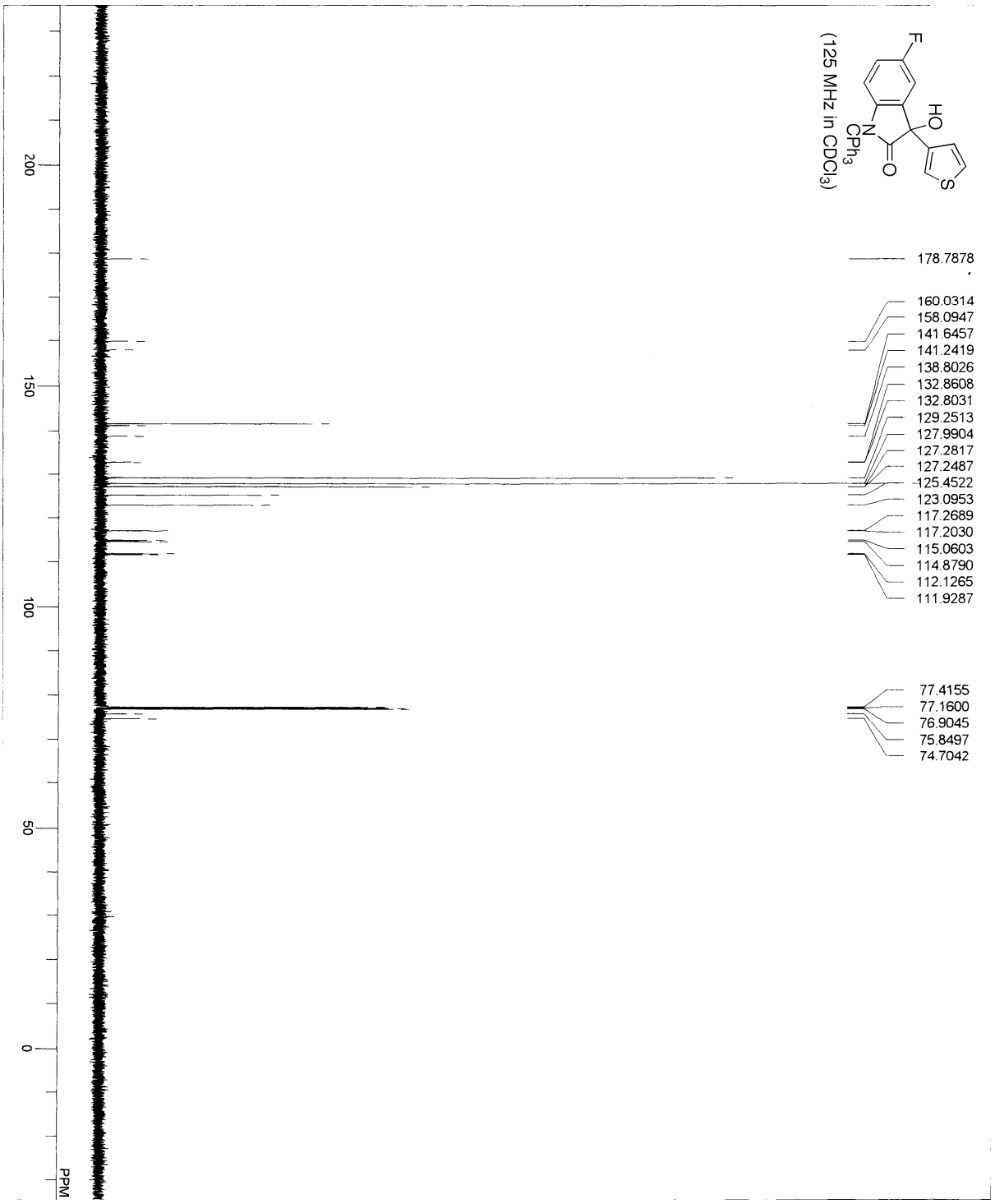

F
HO
N
CPh3
O
Cl
(500 MHz in CDCl3)
10.32
10.26
0.98
1.00
1.00
0.92
10
8
6
4
2
0
PPM

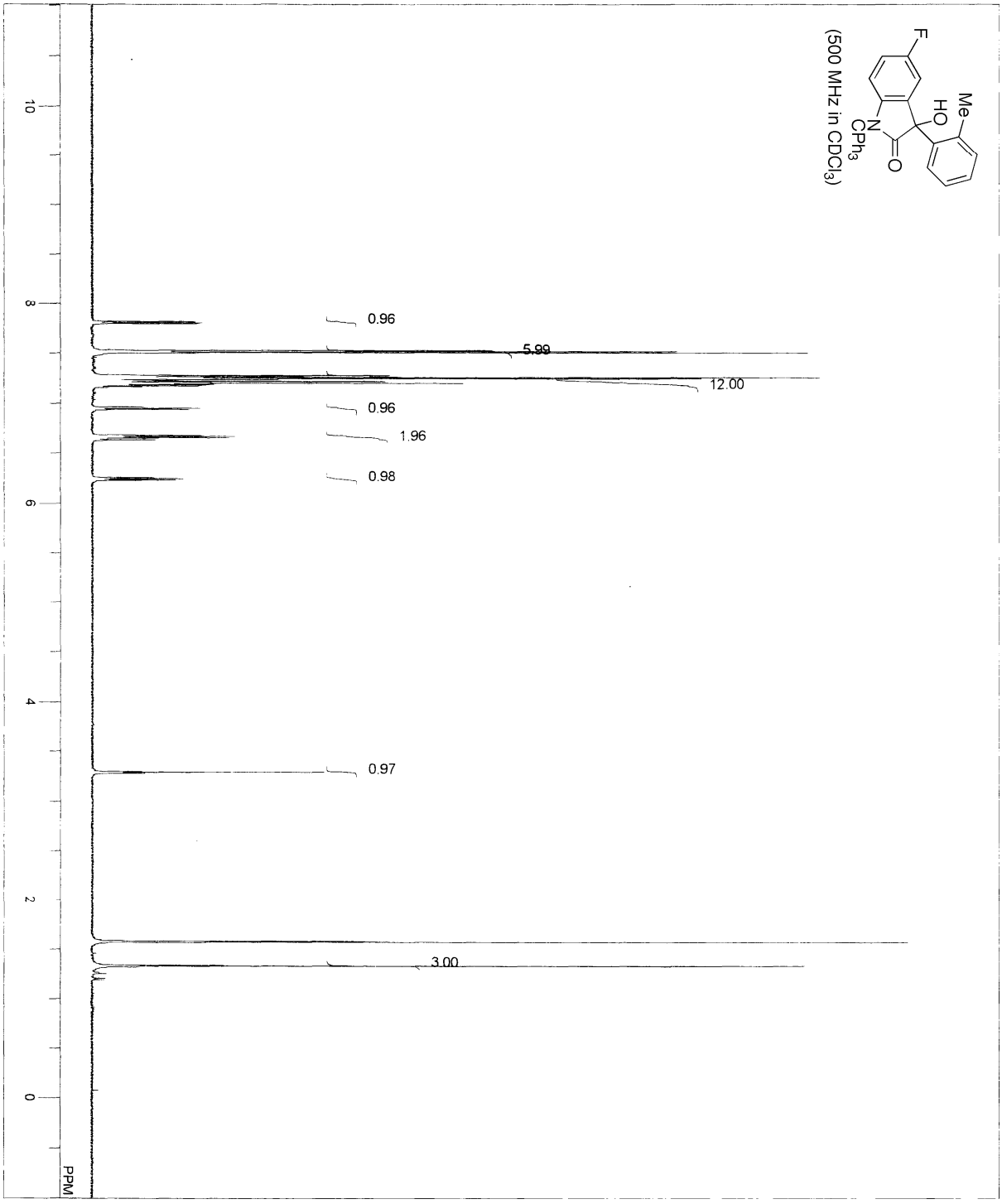

(125 MHz in CDCl3)
F
HO
N
CPh3
O
Cl
178.9444
160.1220
158.1771
141.5551
139.0580
139.0416
138.8191
134.5914
133.2894
133.2317
129.1853
129.0370
129.0040
127.9986
127.2982
126.9850
117.3925
117.3348
115.2251
115.0438
112.3160
112.1265
77.4155
77.1600
76.9045
74.9514
200
150
100
50
0
PPM

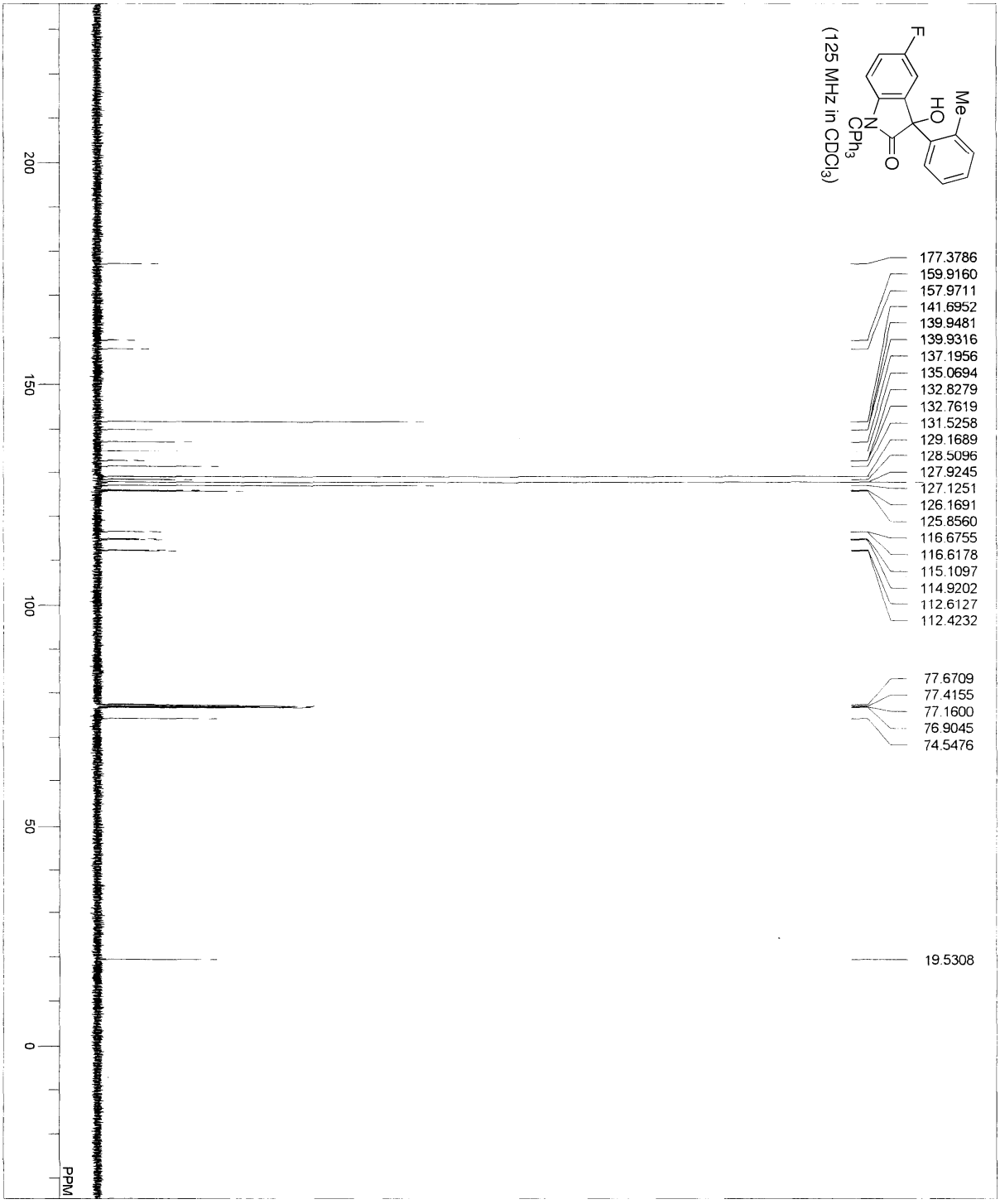

F
HO
N
CPh3
O
(500 MHz in CDCl3)
0.94
2.97
1.01
1.94
5.99
12.29
1.07
0.99
1.00
0.90
10
8
6
4
2
0
PPM

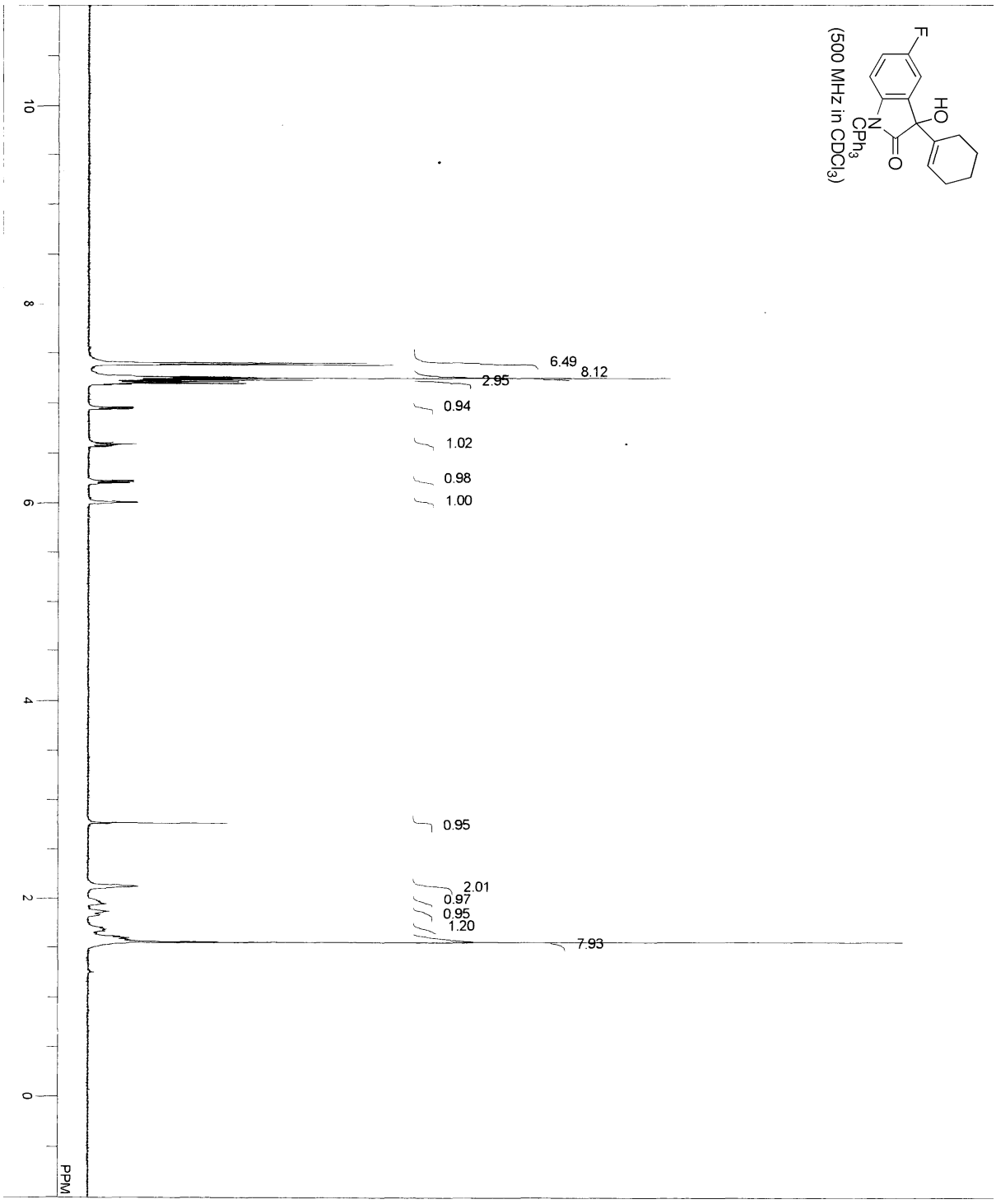

F
HO
N
CPh3
O
(125 MHz in CDCl3)
179.2246
160.0725
158.1359
141.6704
139.1569
139.1322
137.5170
133.6767
133.6190
133.2399
133.2069
129.2265
128.7980
128.4519
127.9492
127.7184
127.2075
126.5894
126.5070
124.6775
123.0870
117.2524
117.1865
115.0438
114.8625
112.4726
112.2748
77.9511
77.4072
77.1600
76.9045
74.9185
200
150
100
50
0
PPM

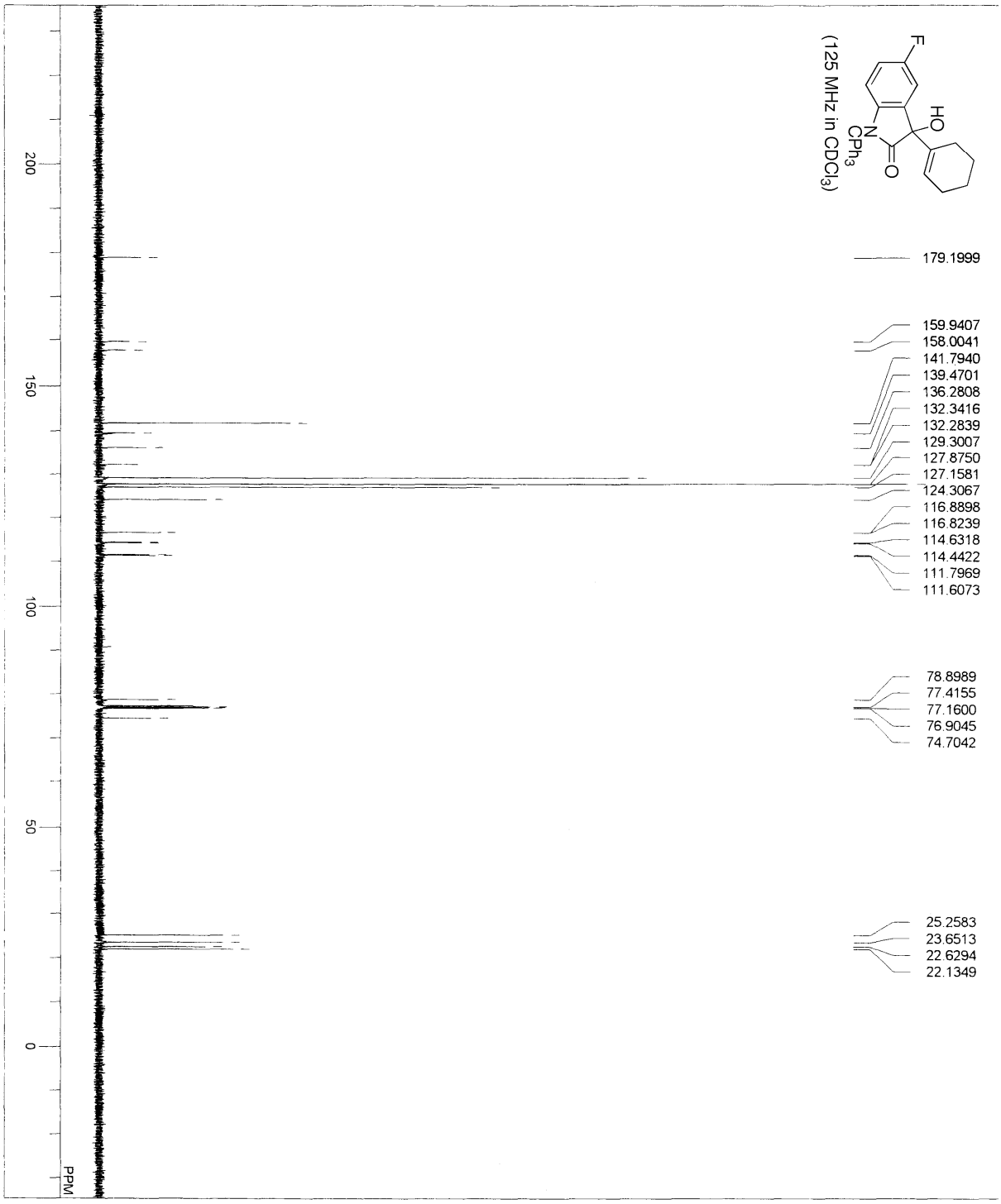

(500 MHz in CDCl3)
F
HO
N
CPh3
O
S
10.32
10.26
0.98
1.00
1.00
0.92
10
8
6
4
2
0
PPM

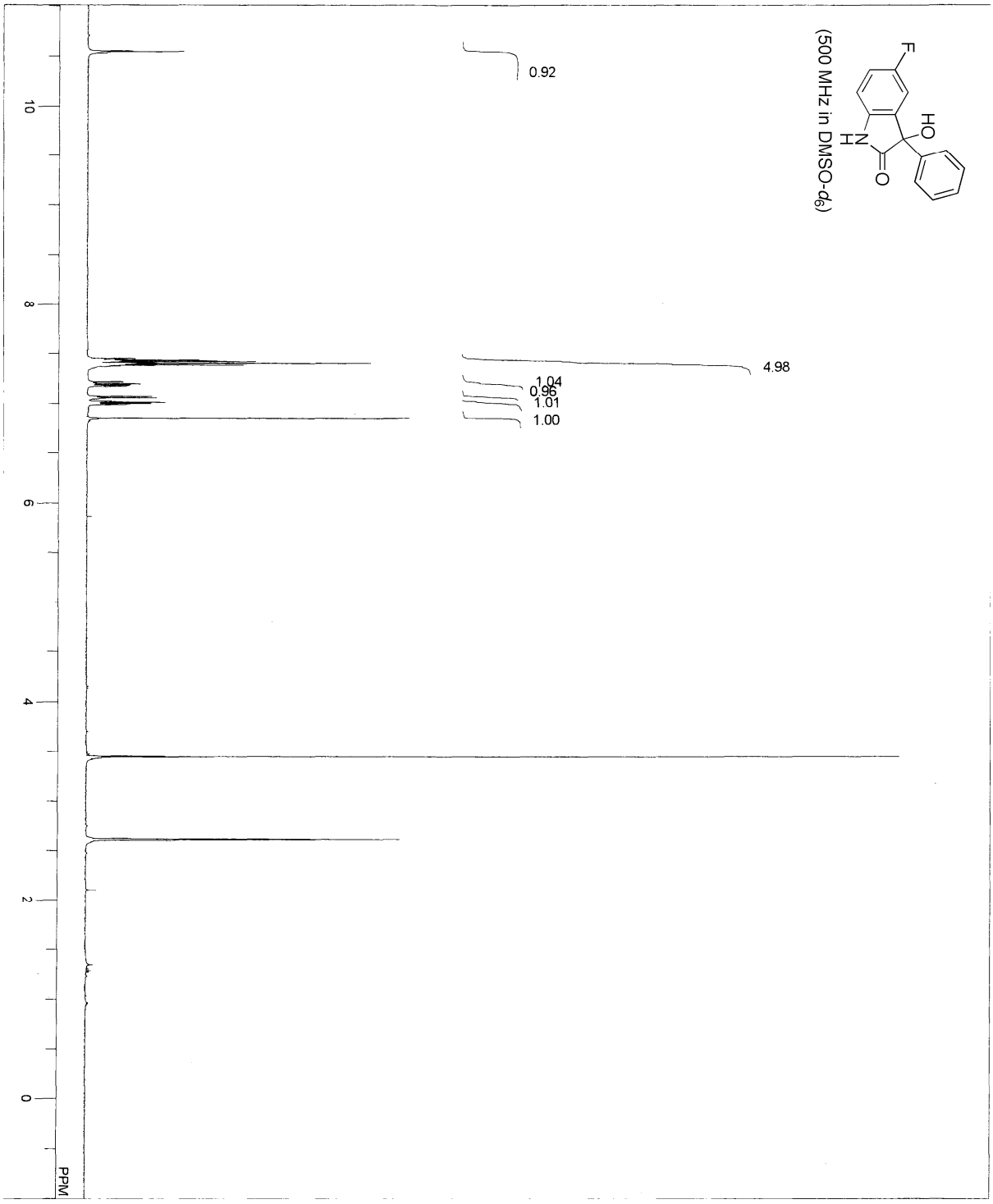

(125 MHz in CDCl3)
F
HO
N
CPh3
O
S
178.7878
160.0314
158.0947
141.6457
141.2419
138.8026
132.8608
132.8031
129.2513
127.9904
127.2817
127.2487
125.4522
123.0953
117.2689
117.2030
115.0603
114.8790
112.1265
111.9287
77.4155
77.1600
76.9045
75.8497
74.7042
200
150
100
50
0
PPM

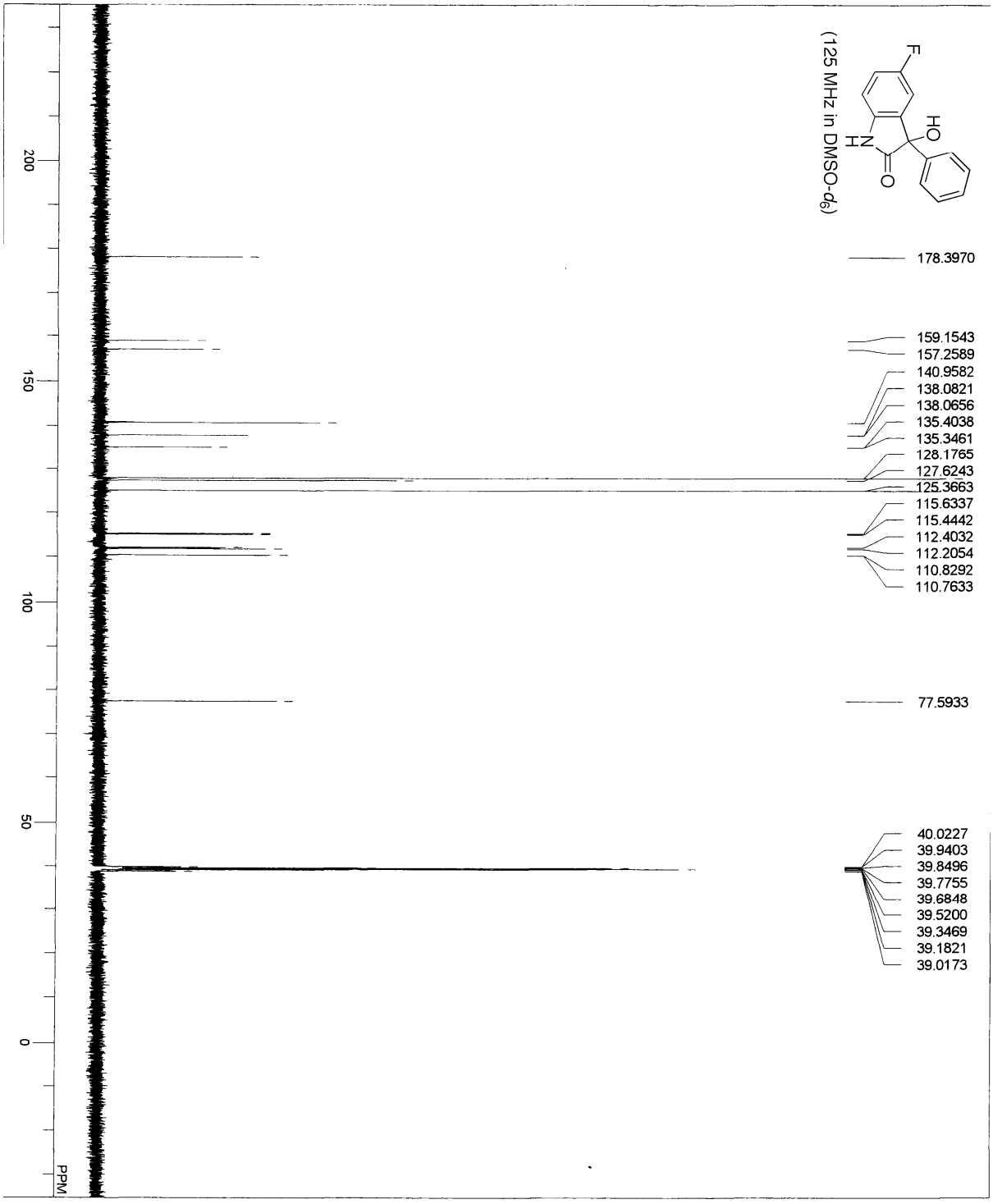

F
Me
HO
N
CPh3
O
(500 MHz in CDCl3)
0.96
5.99
12.00
0.96
1.96
0.98
0.97
3.00
10
8
6
4
2
0
PPM

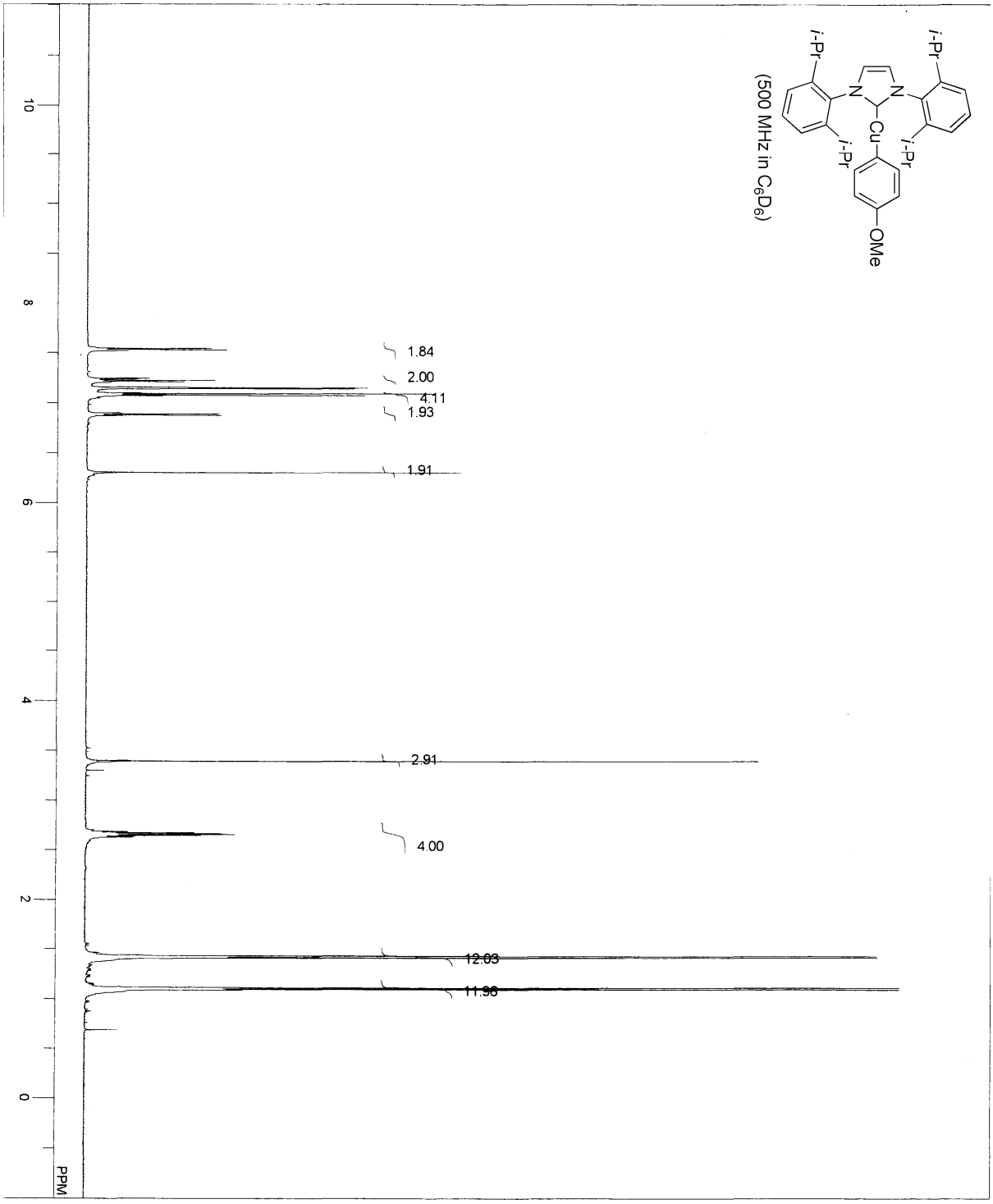

(125 MHz in CDCl3)
F
Me
HO
N
CPh3
O
177.3786
159.9160
157.9711
141.6952
139.9481
139.9316
137.1956
135.0694
132.8279
132.7619
131.5258
129.1689
128.5096
127.9245
127.1251
126.1691
125.8560
116.6755
116.6178
115.1097
114.9202
112.6127
112.4232
77.6709
77.4155
77.1600
76.9045
74.5476
19.5308
200
150
100
50
0
PPM

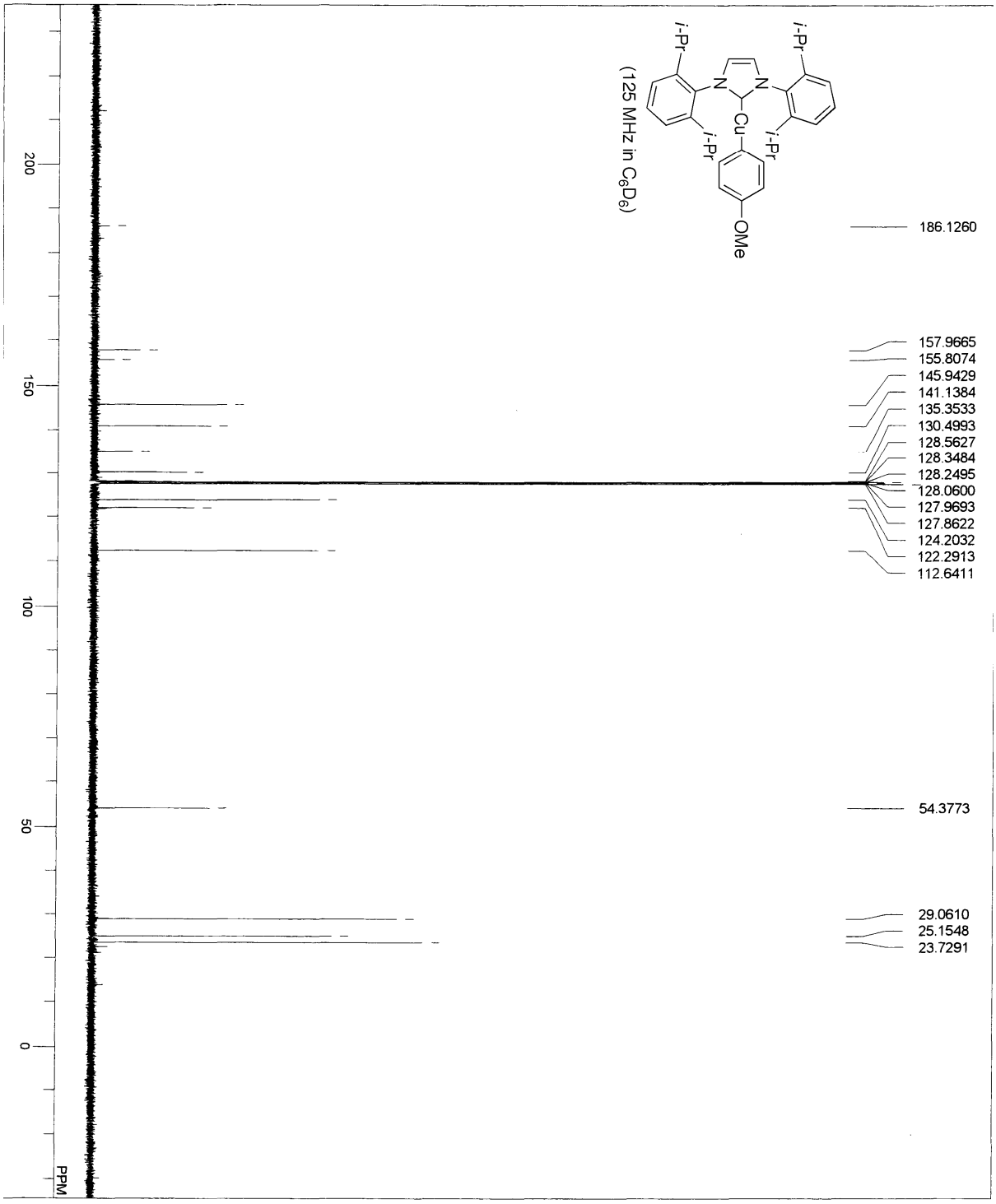

(500 MHz in CDCl3)
F
HO
N
CPh3
O
10
8
6
4
2
0
PPM
6.49
8.12
2.95
0.94
1.02
0.98
1.00
0.95
2.01
0.97
0.95
1.20
7.93

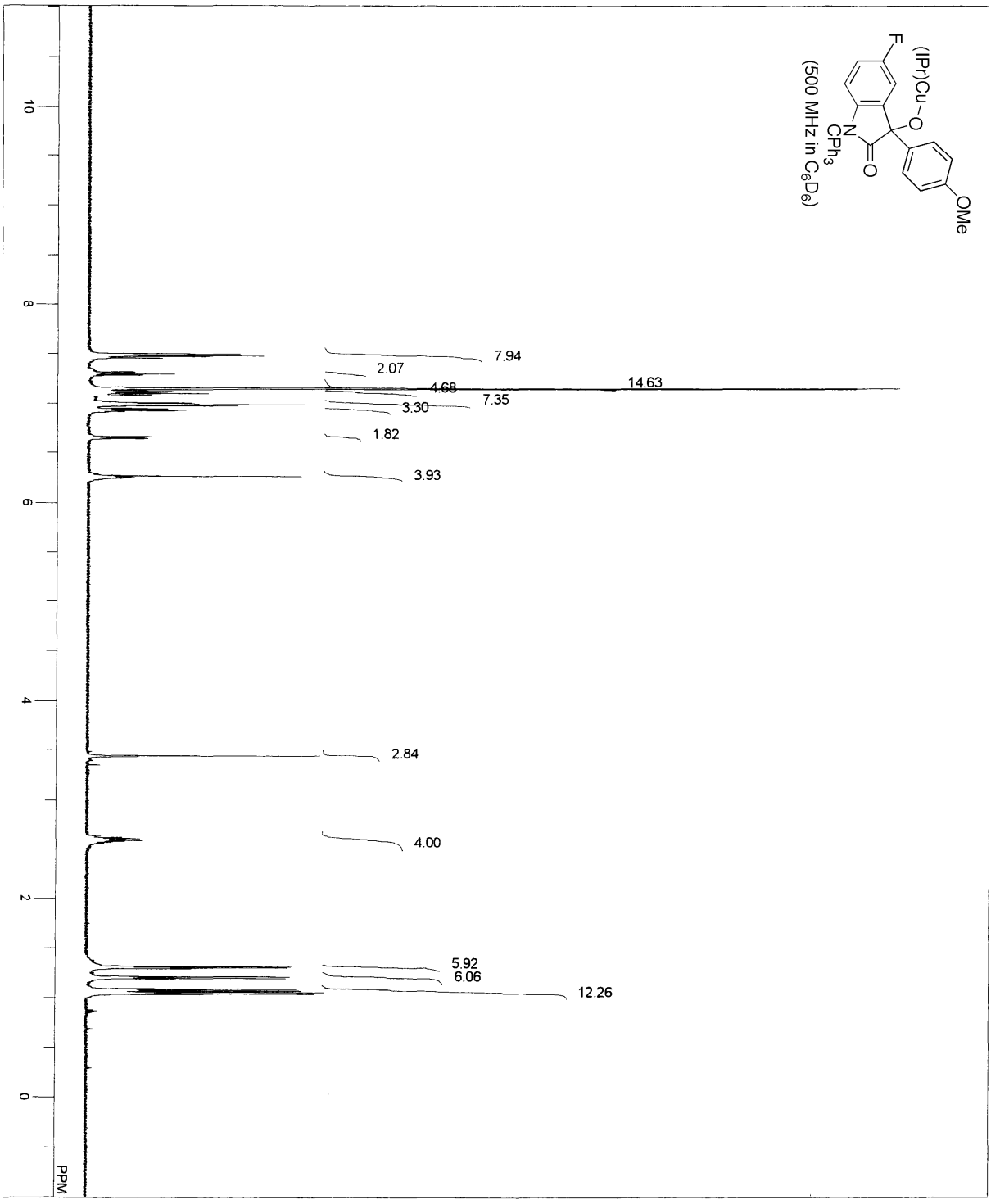

(125 MHz in CDCl3)
F
HO
N
CPh3
O
179.1999
159.9407
158.0041
141.7940
139.4701
136.2808
132.3416
132.2839
129.3007
127.8750
127.1581
124.3067
116.8898
116.8239
114.6318
114.4422
111.7969
111.6073
78.8989
77.4155
77.1600
76.9045
74.7042
25.2583
23.6513
22.6294
22.1349
200
150
100
50
0
PPM

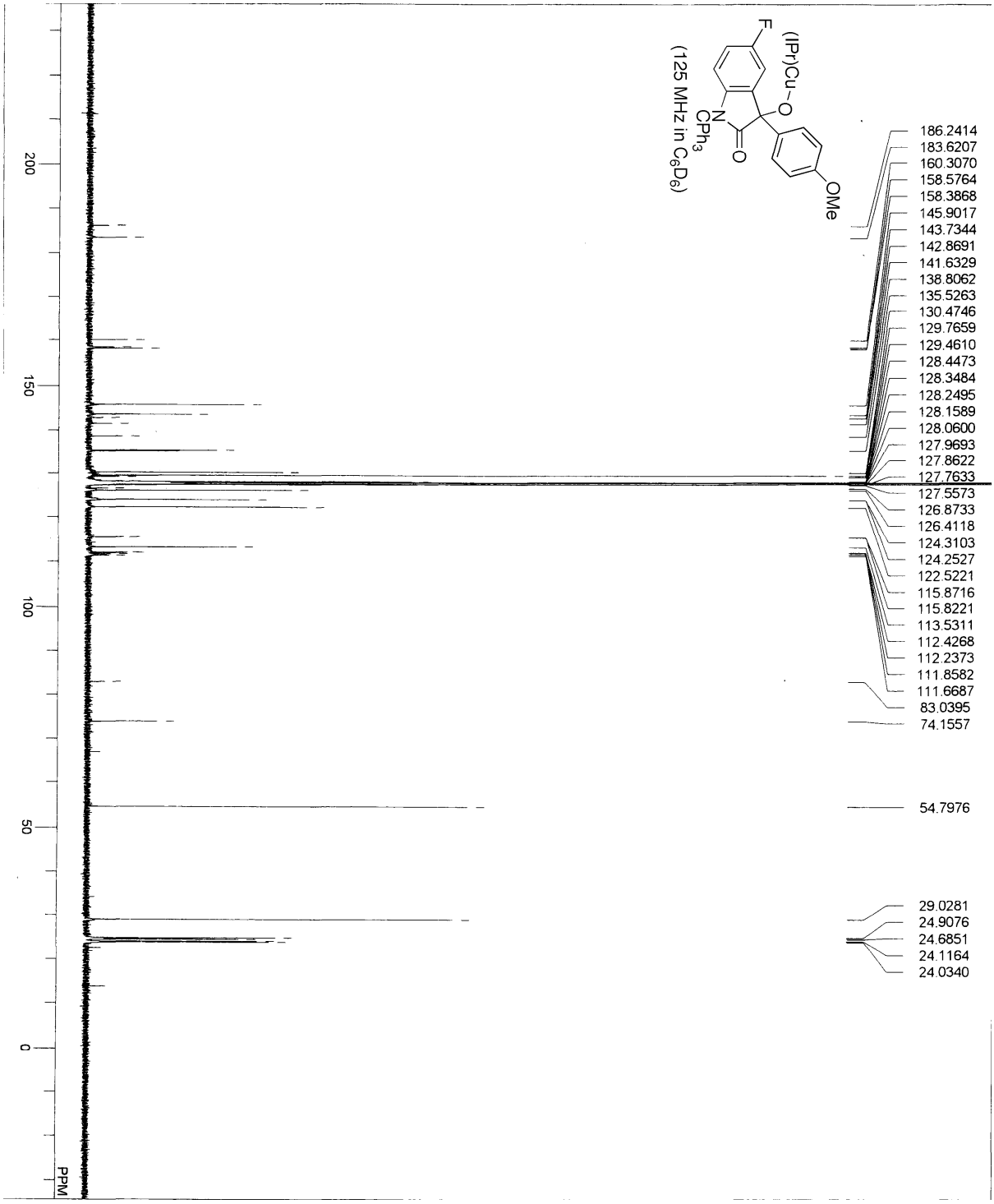

(500 MHz in DMSO-d_6)
F
HO
H
N
O
0.92
4.98
1.04
0.96
1.01
1.00
10
8
6
4
2
0
PPM


(125 MHz in DMSO-d_6)
F
HO
H
N
O
178.3970
159.1543
157.2589
140.9582
138.0821
138.0656
135.4038
135.3461
128.1765
127.6243
125.3663
115.6337
115.4442
112.4032
112.2054
110.8292
110.7633
77.5933
40.0227
39.9403
39.8496
39.7755
39.6848
39.5200
39.3469
39.1821
39.0173
200
150
100
50
0
PPM


(500 MHz in C_6D_6)
i-Pr
i-Pr
i-Pr
i-Pr
N
N
Cu
OMe
1.84
2.00
4.11
1.93
1.91
2.91
4.00
12.03
11.96
PPM
10
8
6
4
2
0


(125 MHz in C_6D_6)
i-Pr
i-Pr
i-Pr
i-Pr
N
N
Cu
OMe
186.1260
157.9665
155.8074
145.9429
141.1384
135.3533
130.4993
128.5627
128.3484
128.2495
128.0600
127.9693
127.8622
124.2032
122.2913
112.6411
54.3773
29.0610
25.1548
23.7291
200
150
100
50
0
PPM


(IPr)Cu–O
F
N
CPh3
O
O
OMe
(500 MHz in C6D6)
7.94
2.07
4.68
14.63
7.35
3.30
1.82
3.93
2.84
4.00
5.92
6.06
12.26
PPM


F
(IPr)Cu–O
N
CPh3
O
O
OMe
(125 MHz in C6D6)
186.2414
183.6207
160.3070
158.5764
158.3868
145.9017
143.7344
142.8691
141.6329
138.8062
135.5263
130.4746
129.7659
129.4610
128.4473
128.3484
128.2495
128.1589
128.0600
127.9693
127.8622
127.7633
127.5573
126.8733
126.4118
124.3103
124.2527
122.5221
115.8716
115.8221
113.5311
112.4268
112.2373
111.8582
111.6687
83.0395
74.1557
54.7976
29.0281
24.9076
24.6851
24.1164
24.0340
200
150
100
50
0
PPM