Mechanistic Insights into Mechanochemical Oxidation of 1,1-Disubstituted Alkenes Mediated by Polymer-Derived Mechanoradicals

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1. General Information

All reagents and solvents were purchased from Sigma-Aldrich, Wako Pure Chemical Industries, Tokyo Chemical Industry, or Kanto Chemical and used as received, unless otherwise noted. ^{1}H and ^{13}C NMR spectra were obtained using a 500 MHz Bruker AVANCE III HD500 spectrometer. Gel permeation chromatography (GPC) measurements were performed in THF at 40 °C on a TOSOH HLC-8320 GPC system equipped with a guard column (TOSOH TSK guard column Super H-L), three columns (TOSOH TSK gel SuperH 6000, 4000, and 2500), a differential refractive index detector, and a UV–vis detector at a flow rate of 0.6 mL/min. The GPC system was calibrated with monodisperse polystyrene standards (M_n = 4430–324200 g/mol; M_w/M_n = 1.03–1.08), and all molecular weight data are reported as polystyrene equivalents. The polystyrene used for ball-milling was purchased from ChemcoPlus (61111, 80323, 507, 30908, and 50828) and used without purification.

2. Synthesis Procedure

2.1 Synthesis of **DAE-OMe/OMe**

Methyl triphenylphosphonium bromide (17.8 g, 49.9 mmol) was added to a round-bottomed flask, and the the flask was purged with nitrogen. Anhydrous THF (100 mL) was added under nitrogen, and the solution was cooled to 0 °C. Potassium *tert*-butoxide (1.0 M in THF, 49.9 mL, 49.9 mmol) was added dropwise at 0 °C, and a yellow suspension was stirred at room temperature for 30 min. To this suspension, a solution of 4,4′-dimethoxybenzophenone (10.1 g, 41.6 mmol) in anhydrous THF (100 mL) was added dropwise at 0 °C, and the reaction mixture was stirred at room temperature for 18 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/dichloromethane = 7/3, v/v) to afford **DAE-OMe/OMe** as a white powder (8.01 g, 80% yield). The spectroscopic data were consistent with those previously reported.[1]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.27 (d, J = 8.9 Hz, 4H), 6.86 (d, J = 8.9 Hz, 4H), 5.30 (s, 2H), 3.83 (s, 6H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 55.30, 111.67, 113.49, 129.43, 134.32, 148.99, 159.31.

2.2 Synthesis of **DAE-SMe/OMe**

First step (compound **1**)

Mg (0.16 g, 6.5 mmol) was placed in a Schlenk tube. The tube was dried with a heat gun under vacuum and backfilled with nitrogen three times. After cooling to room temperature, anhydrous THF (5.0 mL) was added under nitrogen. A solution of 4-bromothioanisole (1.02 g, 5.0 mmol) in anhydrous THF (5.0 mL) was added dropwise at 0 °C, and the mixture was stirred at room temperature for 18 h. A solution of 4'-methoxyacetophenone (1.76 g, 11.7 mmol) in anhydrous THF (5.85 mL) was then added dropwise at 0 °C under nitrogen, and the reaction mixture was stirred at room temperature for 16 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 7/3, v/v) to afford compound **1** as a colorless oil (1.11 g, 81% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.33–7.30 (m, 4H), 7.20 (d, J = 8.5 Hz, 2H), 6.84 (d, J = 8.9 Hz, 2H), 3.79 (s, 3H), 2.47 (s, 3H), 2.09 (s, 1H), 1.91 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 15.88, 30.96, 55.26, 75.71, 113.48, 126.35, 126.37, 127.10, 136.83, 140.13, 145.34, 158.56.

ESI-TOF MS (*m/z*): $[M+Na]^+$ calcd. for $C_{16}H_{18}NaO_2S$, 297.0925; Found, 297.0920.

Second step (**DAE-SMe/OMe**)

Compound **1** (0.71 g, 2.6 mmol) and *p*-toluenesulfonic acid monohydrate (24 mg, 0.13 mmol) were added to anhydrous toluene (8.0 mL), and the solution was heated at 70 °C for 3 h. After cooling to room temperature, saturated aqueous $NaHCO_3$ was added to the reaction mixture. The mixture was extracted with dichloromethane, and the organic layer was dried over $MgSO_4$. The filtrate was concentrated under reduced pressure, and the crude product was purified by silica gel column chromatography (hexane/dichloromethane = 8/2, v/v) to afford **DAE-SMe/OMe** as a white powder (0.58 g, 89% yield). The spectroscopic data were consistent with those previously reported.[2]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.28–7.25 (m, 4H), 7.21 (d, $J = 8.6$ Hz, 2H), 6.87 (d, $J = 8.6$ Hz, 2H), 5.35 (d, $J = 1.3$ Hz, 1H), 5.34 (d, $J = 1.3$ Hz, 1H), 3.83 (s, 3H), 2.50 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 15.82, 55.31, 112.58, 113.56, 126.22, 128.72, 129.42, 133.89 137.90, 138.65, 148.93, 159.39.

2.3 Synthesis of **DAE-H/OMe**

Methyl triphenylphosphonium bromide (6.12 g, 17.1 mmol) was added to a round-bottomed flask, and the flask was purged with nitrogen. Anhydrous THF (17 mL) was added under nitrogen, and the solution was cooled to 0 °C. Potassium *tert*-butoxide (1.0 M in THF, 17.1 mL, 17.1 mmol) was added dropwise at 0 °C, and the resulting yellow suspension was stirred at room temperature for 30 min. To this suspension, a solution of 4-methoxybenzophenone (3.03 g, 14.3 mmol) in anhydrous THF (40.0 mL) was added dropwise at 0 °C, and the reaction mixture was stirred at room temperature for 12 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/dichloromethane = 8/2, v/v) to afford **DAE-H/OMe** as a white powder (2.52 g, 84% yield). The spectroscopic data were consistent with those previously reported.[2]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.36–7.30 (m, 5H), 7.28 (d, $J = 8.9$ Hz, 2H), 6.87 (d, $J = 8.9$ Hz, 2H), 5.40 (d, $J = 1.3$ Hz, 1H), 5.35 (d, $J = 1.3$ Hz, 1H), 3.83 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 55.31, 112.95, 113.54, 127.65, 128.13, 128.33, 129.40, 134.02, 141.85, 149.54, 159.36.

2.4 Synthesis of **DAE-*t*Bu/*t*Bu**

First step (compound **2**)

Mg (1.17 g, 47.9 mmol) was placed in a Schlenk tube. The tube was dried with a heat gun under vacuum and backfilled with nitrogen three times. After cooling to room temperature, anhydrous THF (30 mL) was added under nitrogen. A solution of 1-bromo-4-*tert*-butylbenzene (7.84 g, 36.8 mmol) in anhydrous THF (20 mL) was added dropwise at 0 °C, and the mixture was stirred at room temperature for 4 h. Ethyl acetate (1.83 mL, 18.8 mmol) was then added dropwise at 0 °C under nitrogen, and the reaction mixture was stirred at room temperature for 3 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane) to afford compound **2** as a white powder (4.98 g, 87% yield). The spectroscopic data were consistent with those previously reported.[3]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.35–7.31 (m, 8H), 2.12 (s, 1H), 1.93 (s, 3H), 1.30 (s, 18H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 30.98, 31.38, 34.42, 75.93, 125.02, 125.52, 145.15, 149.64.

Second step (**DAE-*t*Bu/*t*Bu**)

Compound **2** (4.98 g, 16.0 mmol) and *p*-toluenesulfonic acid monohydrate (914 mg, 4.8 mmol) were added to anhydrous toluene (50.0 mL), and the solution was heated at 70 °C for 3 h. After cooling to room temperature, saturated aqueous $NaHCO_3$ was added to the reaction mixture. The mixture was extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$. After filtration, the solution was concentrated under reduced pressure, and the crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 19/1, v/v) to afford **DAE-*t*Bu/*t*Bu** as a white powder (4.26 g, 90% yield). The spectroscopic data were consistent with those previously reported.[4]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.35 (d, J = 8.6 Hz, 4H), 7.29 (d, J = 8.6 Hz, 4H), 5.41 (s, 2H), 1.34 (s, 18H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 31.36, 34.56, 113.16, 125.00, 127.94, 138.65, 149.57, 150.63.

2.5 Synthesis of **DAE-SMe/SMe**

First step (compound **3**)

Mg (1.09 g, 44.8 mmol) was placed in a Schlenk tube. The tube was dried with a heat gun under vacuum and backfilled with nitrogen three times. After cooling to room temperature, anhydrous THF (20 mL) was added under nitrogen. A solution of 4-bromothioanisole (7.00 g, 34.5 mmol) in anhydrous THF (24 mL) was added dropwise at 0 °C, and the mixture was stirred at room temperature for 4 h. Ethyl acetate (1.72 mL, 17.6 mmol) was then added dropwise at 0 °C under nitrogen, and the reaction mixture was stirred at room temperature for 16 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 7/3, v/v) to afford compound **3** as a white powder (4.25 g, 85% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.32 (d, J = 8.7 Hz, 4H), 7.20 (d, J = 8.7 Hz, 4H), 2.46 (s, 6H), 2.19 (s, 1H), 1.90 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 15.84, 30.77, 75.75, 126.39, 126.40, 137.11, 144.86

ESI-TOF MS (*m/z)*: $[M+Na]^+$ calcd. for $C_{16}H_{18}NaOS_2$, 313.0697; Found, 313.0691.

Second step (**DAE-SMe/SMe**)

Compound **3** (4.65 g, 16.0 mmol) and *p*-toluenesulfonic acid monohydrate (152 mg, 0.80 mmol) were added to anhydrous toluene (50.0 mL), and the solution was heated at 70 °C for 3 h. After cooling to room temperature, saturated aqueous $NaHCO_3$ was added to the reaction mixture. The mixture was extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$. After filtration, the filtrate was concentrated under reduced pressure, and the crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 19/1, v/v) to afford **DAE-SMe/SMe** as a white powder (1.82 g, 42% yield). The spectroscopic data were consistent with those previously reported.[4]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.26 (d, J = 8.6 Hz, 4H), 7.21 (d, J = 8.7 Hz, 4H), 5.40 (s, 2H), 2.50 (s, 6H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 15.78, 113.49, 126.2, 128.68, 138.12, 138.18, 148.86.

2.6 Synthesis of **DAE-CF_3/OMe**

Methyl triphenylphosphonium bromide (4.62 g, 12.9 mmol) was added to a round-bottomed flask, and the flask was purged with nitrogen. Anhydrous THF (62.5 mL) was added under nitrogen, and the solution was cooled to 0 °C. Potassium *tert*-butoxide (1.0 M in THF, 13.0 mL, 13.0 mmol) was added dropwise at 0 °C, and the resulting yellow suspension was stirred at room temperature for 30 min. To this suspension, a solution of 4-methoxy-4'-trifluoromethylbenzophenone (3.02 g, 10.8 mmol) in anhydrous THF (11.0 mL) was added dropwise at 0 °C, and the reaction mixture was further stirred at room temperature for 16 h. The reaction was quenched with saturated aqueous NH_4Cl, and the reaction mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/dichloromethane = 8/2, v/v) to afford **DAE-CF_3/OMe** as a white powder (2.83 g, 94% yield). The spectroscopic data were consistent with those previously reported.[5]

^1H NMR (500 MHz, $CDCl_3$): δ/ppm 7.59 (d, J = 8.1 Hz, 2H), 7.45 (d, J = 8.0 Hz, 2H), 7.26–7.22 (m, 2H), 6.89–6.85 (m, 2H), 5.49 (d, J = 1.0 Hz, 2H), 5.40 (d, J = 0.9 Hz, 2H), 3.83 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 55.32, 113.74, 114.48, 124.25 (q, J = 270.1 Hz), 125.13 (q, J = 3.8 Hz), 128.62, 129.32, 129.70 (q, J = 32.0 Hz), 133.14, 145.48, 148.46, 159.61.

2.7 Synthesis of **DAE-Ac/OMe**

First step (compound **4**)

4'-Bromoacetophenone (5.97 g, 30.0 mmol), *p*-toluenesulfonic acid monohydrate (56.5 mg, 0.30 mmol, 1 mol%) and 2,2-dimethyl-1,3-propanediol (4.69 g, 45.0 mmol) were dissolved in anhydrous toluene (50 mL), and the reaction mixture was heated to reflux with a Dean–Stark apparatus for 18 h. After cooling to 0 °C, the reaction was quenched with saturated aqueous $NaHCO_3$, and the mixture was extracted with ethyl acetate. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 9/1, v/v) to afford compound **4** as a colorless oil (7.97 g, 93% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.50 (d, *J* = 8.6 Hz, 2H), 7.30 (d, *J* = 8.5 Hz, 2H), 3.37 (s, 4H), 1.50 (s, 3H), 1.25 (s, 3H), 0.59 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 21.84, 22.80, 71.68, 99.84, 121.69, 128.64, 131.80, 140.13.

ESI-TOF MS (*m/z)*: $[M+Na]^+$ calcd. for $C_{13}H_{17}BrNaO_2$, 307.0310; Found, 307.0304.

Second step (compound **5**)

Mg (534 mg, 21.9 mmol) was placed in a Schlenk tube. The tube was dried with a heat gun under vacuum and backfilled with nitrogen three times. After cooling to room temperature, anhydrous THF (11.0 mL) was added under nitrogen. A solution of compound **4** (4.82 g, 16.9 mmol) in anhydrous THF (6.0 mL) was added dropwise at 0 °C, and the mixture was stirred at 60 °C for 24 h. A solution of 4’-methoxyacetophenone (2.55 g, 17.0 mmol) in anhydrous THF (8.5 mL) was then added dropwise at 0 °C under nitrogen, and the reaction mixture was stirred at room temperature for 8 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with ethyl acetate. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 8/2, v/v) to afford compound **5** as a colorless oil (3.39 g, 56% yield).

^{1}H NMR (500 MHz, CDCl$_3$): δ/ppm 7.41 (d, *J* = 8.6 Hz, 2H), 7.38–7.34 (m, 4H), 6.86 (d, *J* = 8.9 Hz, 2H), 3.80 (s, 3H), 3.43 (d, *J* = 11.1 Hz, 2H), 3.36 (d, *J* = 11.1 Hz, 2H), 2.17 (s, 1H), 1.95 (s, 3H), 1.51 (s, 3H), 1.25 (s, 3H), 0.59 (s, 3H).

^{13}C NMR (125 MHz, CDCl$_3$): δ/ppm 21.88, 22.86, 29.98, 31.12, 31.94, 55.26, 71.70, 75.85, 100.16, 113.48, 126.04, 126.56, 127.09, 139.48, 140.21, 147.59, 158.54.

ESI-TOF MS (*m/z)*: [M+Na]$^+$ calcd. for $C_{22}H_{28}NaO_4$, 379.1885; Found, 379.1880.

Third step (compound **6**)

Compound **5** (3.39 g, 9.51 mmol) was dissolved in THF (9.5 mL) and H_2O (9.5 mL), and then 1M HCl (0.95 mL) was added dropwise at room temperature. After stirring at room temperature for 15 h, the reaction mixture was poured into saturated aqueous $NaHCO_3$. The reaction mixture was extracted with dichloromethane, and the organic layer was dried over $MgSO_4$. After filtration, the filtrate was concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 6/4, v/v) to afford compound **6** as a colorless oil (2.28 g, 89% yield).

^{1}H NMR (500 MHz, CDCl$_3$): δ/ppm 7.89 (d, *J* = 8.5 Hz, 2H), 7.50 (d, *J* = 8.5 Hz, 2H), 7.31 (d, *J* = 8.9 Hz, 2H), 6.84 (d, *J* = 8.9 Hz, 2H), 3.78 (s, 3H), 2.57 (s, 3H), 2.35 (s, 1H), 1.94 (s, 3H).

^{13}C NMR (125 MHz, CDCl$_3$): δ/ppm 26.60, 30.74, 55.26, 75.81, 113.66, 125.91, 127.16, 128.27, 135.61, 139.47, 153.66, 158.76, 197.83.

ESI-TOF MS (*m/z)*: [M+Na]$^+$ calcd. for $C_{17}H_{18}NaO_3$, 293.1154; Found, 293.1148.

Fourth step (**DAE-Ac/OMe**)

Compound **6** (2.28 g, 8.4 mmol) and *p*-toluenesulfonic acid monohydrate (92 mg, 0.48 mmol) were added to anhydrous toluene (40.0 mL) and heated at 70 °C for 3 h. After cooling to room temperature, saturated aqueous $NaHCO_3$ was added to the reaction mixture. The mixture was extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$. After filtration, the solution was concentrated under reduced pressure, and the crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 7/3, v/v) to afford **DAE-Ac/OMe** as a white powder (1.97 g, 92% yield). The spectroscopic data were consistent with those previously reported.[6]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.93 (d, J = 8.5 Hz, 2H), 7.43 (d, J = 8.5 Hz, 2H), 7.24 (d, J = 8.8 Hz, 4H), 6.88 (d, J = 8.9 Hz, 4H), 5.49 (d, J = 0.9 Hz, 1H), 5.44 (d, J = 1.0 Hz, 1H), 3.83 (s, 3H), 2.62 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 26.65, 55.33, 113.71, 114.62, 128.30, 128.47, 129.36, 133.22, 136.31, 146.63, 148.71, 159.57, 197.73.

2.8 Synthesis of **DAE-Ac/Ac**

First step (compound **7**)

Mg (697 mg, 28.7 mmol) was placed in a Schlenk tube. The tube was dried with a heat gun under vacuum and backfilled with nitrogen three times. After cooling to room temperature, anhydrous THF (11.0 mL) was added under nitrogen. A solution of compound **4** (6.37 g, 22.3 mmol) in anhydrous THF (11.0 mL) was added dropwise at 0 °C, and the mixture was stirred at 60 °C for 24 h. Ethyl acetate (1.10 mL, 11.2 mmol) was then added dropwise at 0 °C under nitrogen, and the reaction mixture was stirred at room temperature for 16 h. The reaction was quenched with saturated aqueous NH_4Cl, and the mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 8/2, v/v) to afford compound **7** as a white powder (4.75 g, 95% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.44 (d, J = 8.5 Hz, 2H), 7.38 (d, J = 8.5 Hz, 2H), 3.45 (d, J = 10.8 Hz, 4H), 3.38 (d, J = 11.0 Hz, 4H), 2.23 (s, 1H), 1.99 (s, 3H), 1.53 (s, 6H), 1.26 (s, 6H), 0.60 (s, 6H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 21.91, 22.85, 29.99, 31.17, 31.86, 71.72, 76.12, 100.12, 126.15, 126.60, 139.74, 147.16.

ESI-TOF MS (*m/z)*: $[M+Na]^+$ calcd. for $C_{28}H_{38}NaO_5$, 477.2617; Found, 477.2611.

Second step (compound **8**)

Compound **7** (4.29 g, 9.44 mmol) was dissolved in THF (20.0 mL) and H_2O (20.0 mL), and then 1M HCl (0.94 mL) was added dropwise at room temperature. After stirring at room temperature for 15 h, the reaction mixture was poured into saturated aqueous $NaHCO_3$. The reaction mixture was extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$. After filtration, the filtrate was concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 5/5, v/v) to afford compound **8** as a white powder (1.59 g, 59% yield).

^1H NMR (500 MHz, $CDCl_3$): δ/ppm 7.85 (d, *J* = 8.5, 4H), 7.49 (d, *J* = 8.5, 4H), 3.18 (s, 1H), 2.52 (s, 6H), 1.97 (s, 3H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 26.60, 30.35, 75.82, 126.02, 128.44, 135.83, 152.60, 197.92.

ESI-TOF MS (*m/z)*: $[M+Na]^+$ calcd. for $C_{18}H_{18}NaO_3$, 305.1154; Found, 305.1148.

Third step (**DAE-Ac/Ac**)

Compound **8** (1.50 g, 5.30 mmol) and *p*-toluenesulfonic acid monohydrate (50.0 mg, 0.26 mmol) were added to anhydrous toluene (26.5 mL), and the solution was heated at 70 °C for 3 h. After cooling to room temperature, saturated aqueous $NaHCO_3$ was added to the reaction mixture. The mixture was extracted with dichloromethane, and the organic layer was dried over $MgSO_4$. After filtration, the filtrate was concentrated under reduced pressure, and the crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 8/2, v/v) to afford **DAE-Ac/Ac** as a white powder (1.18 g, 84% yield).

^1H NMR (500 MHz, $CDCl_3$): δ/ppm 7.94 (d, *J* = 8.6 Hz, 4H), 7.41 (d, *J* = 8.6 Hz, 4H), 5.65 (s, 2H), 2.62 (s, 6H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 26.66, 117.61, 128.38, 128.47, 136.60, 145.40, 148.40, 197.59.

ESI-TOF MS (*m/z)*: $[M+Na]^+$ calcd. for $C_{18}H_{16}NaO_2$, 287.1048; Found, 287.1043.

2.9 Synthesis of **DAE-CN/CN**

Methyl triphenylphosphonium bromide (5.59 g, 15.6 mmol) was added to a round-bottomed flask, and the atmosphere was replaced with nitrogen. Anhydrous THF (16 mL) was added under nitrogen, and the solution was cooled to 0 °C. Potassium *tert*-butoxide (1.0 M in THF, 15.6 mL, 15.6 mmol) was added dropwise at 0 °C, and the resulting yellow suspension was stirred at room temperature for 30 min. To this suspension, a solution of 4,4′-dicyanobenzophenone (3.03 g, 13.0 mmol) in anhydrous THF (10.0 mL) was added dropwise at 0 °C, and the reaction mixture was further stirred at room temperature for 16 h. The reaction was quenched with saturated aqueous NH_4Cl, and the reaction mixture was extracted with dichloromethane. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 9/1, v/v) to afford **DAE-CN/CN** as a white powder (1.26 g, 42% yield). The spectroscopic data were consistent with those previously reported.[7]

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.67 (d, J = 8.6 Hz, 4H), 7.40 (d, J = 8.6 Hz, 4H), 5.68 (s, 2H).

^{13}C NMR (125 MHz, $CDCl_3$): δ/ppm 112.07, 118.54, 119.11, 128.78, 132.37, 144.69, 147.32.

2.10 Corey-Chaykovsky reactions of DAK derivatives

Sodium hydride (2.2 mmol, 60 wt% dispersion in mineral oil) was added to a round-bottomed flask, and the atmosphere was replaced with nitrogen. Anhydrous DMSO (2.0 mL) was added, and the mixture was stirred at room temperature for 10 min. Under ice cooling and nitrogen, a solution of trimethylsulfonium iodide (2.2 mmol) in anhydrous DMSO (4.0 mL) was added dropwise over 10 min. The resulting mixture was stirred under ice-cooling for an additional 15 min. Subsequently, a solution of the diaryl ketone derivative (0.90 mmol) in anhydrous THF (6.0 mL) was added dropwise over 15 min, and the reaction mixture was stirred at room temperature for 14 h. The reaction mixture was poured into ice-cooled water and extracted with hexane/ethyl acetate (3/1, v/v). The organic layer was dried over anhydrous $MgSO_4$, filtered, and concentrated under reduced pressure to afford the crude product.

DAO-*t*Bu/*t*Bu (crude product)

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.36 (d, *J* = 8.6 Hz, 4H), 7.28 (d, *J* = 8.6 Hz, 4H), 3.27 (s, 2H), 1.31 (s, 18H).

DAO-CN/CN

The crude product was purified by silica gel column chromatography (hexane/ethyl acetate = 8/2, v/v) to afford **DAO-CN/CN** as a white powder (87% yield).

^{1}H NMR (500 MHz, $CDCl_3$): δ/ppm 7.67 (d, *J* = 8.6 Hz, 4H), 7.45 (d, *J* = 8.7 Hz, 4H), 3.31 (s, 2H).

^{13}C NMR (125 MHz, CDCl3): δ/ppm 56.92, 60.86, 112.60, 118.24, 128.14, 132.43, 143.26

ESI-TOF MS (*m/z*): $[M+Na]^+$ calcd. for $C_{16}H_{10}N_2NaO$, 269.0691; Found, 269.0685.

3. ^{1}H NMR and ^{13}C NMR spectra

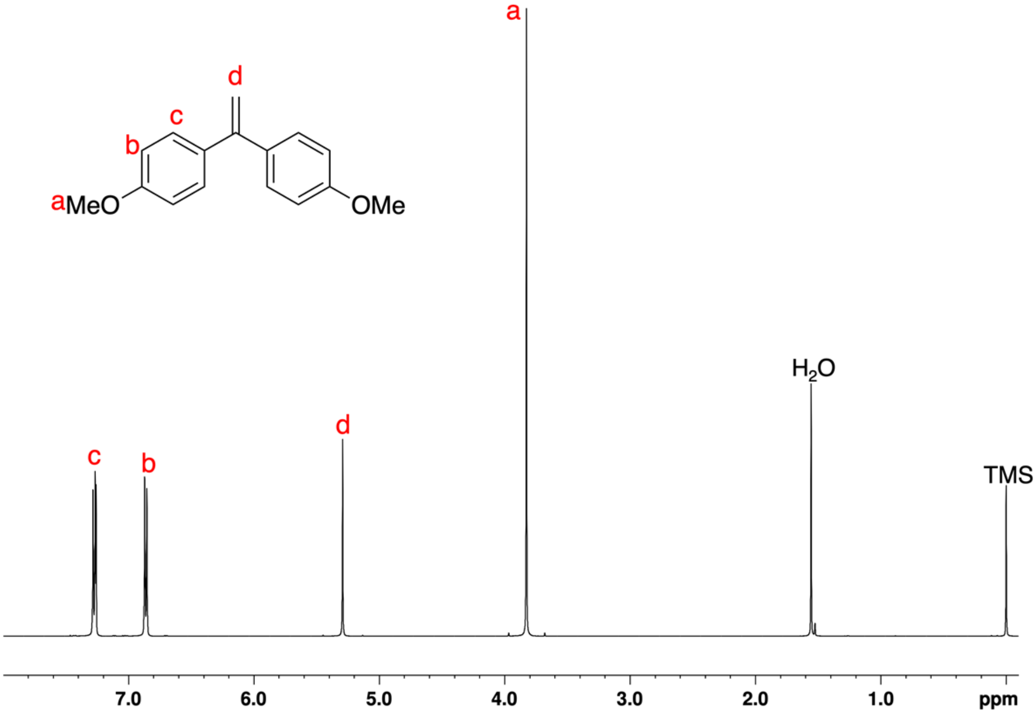

Figure S1. ^{1}H NMR spectrum of **DAE-OMe/OMe** ($CDCl_3$, 500 MHz).

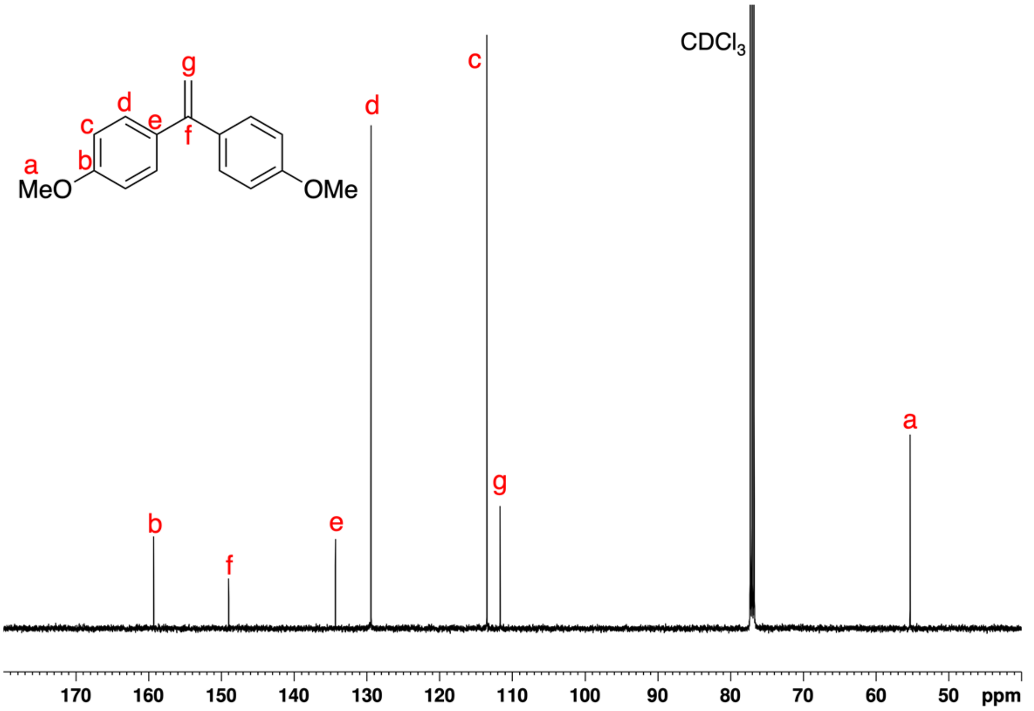

Figure S2. ^{13}C NMR spectrum of **DAE-OMe/OMe** ($CDCl_3$, 125 MHz).

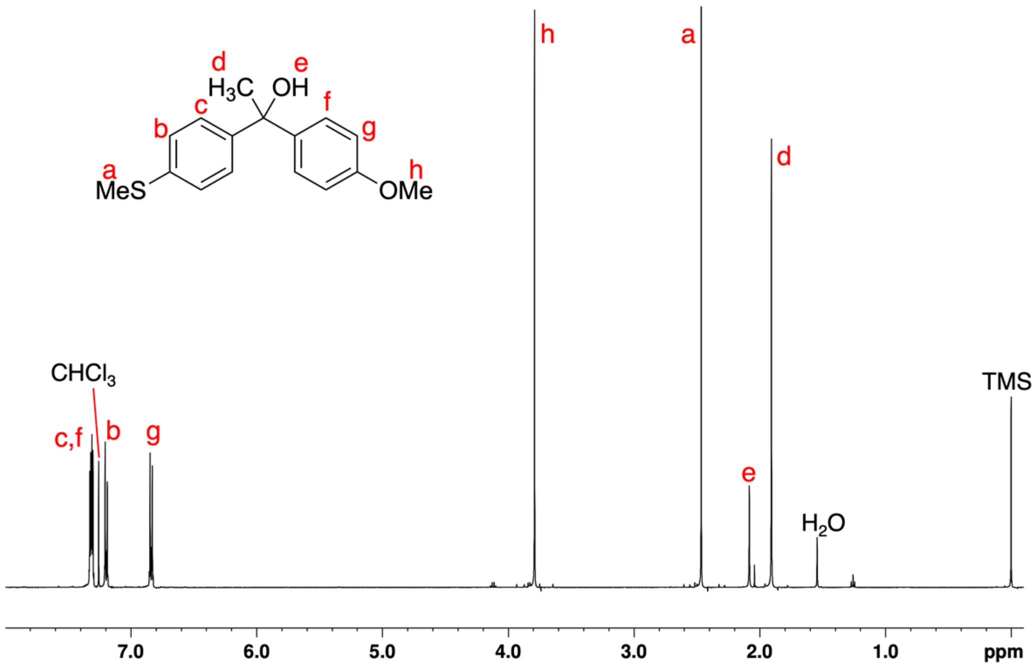

Figure S3. ^{1}H NMR spectrum of compound **1** ($CDCl_3$, 500 MHz).

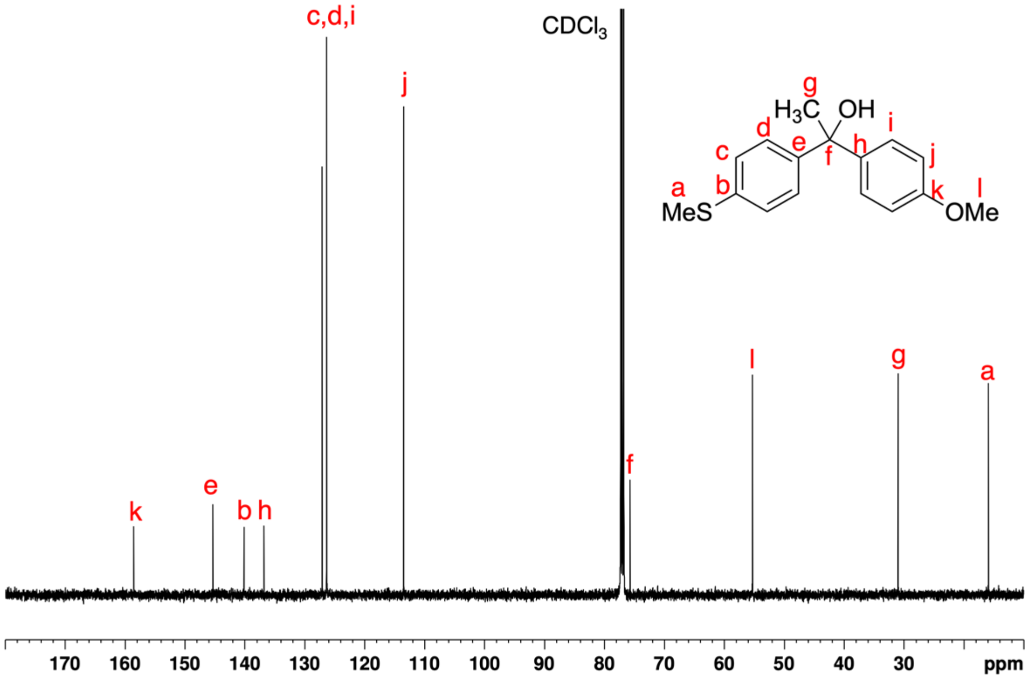

Figure S4. ^{13}C NMR spectrum of compound **1** ($CDCl_3$, 125 MHz).

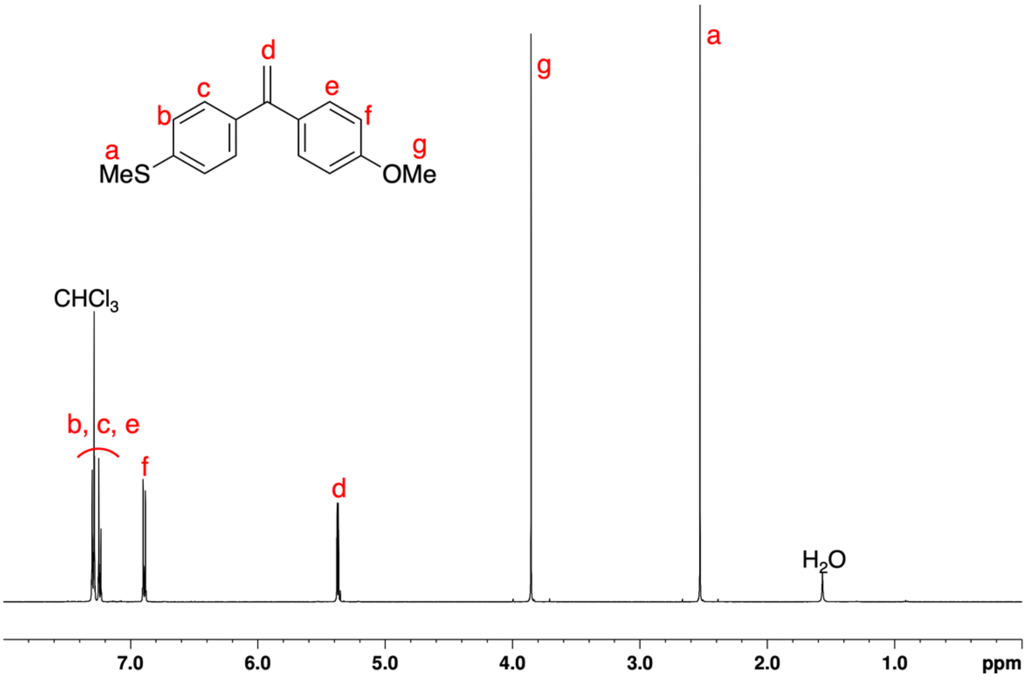

Figure S5. ^{1}H NMR spectrum of **DAE-SMe/OMe** ($CDCl_3$, 500 MHz).

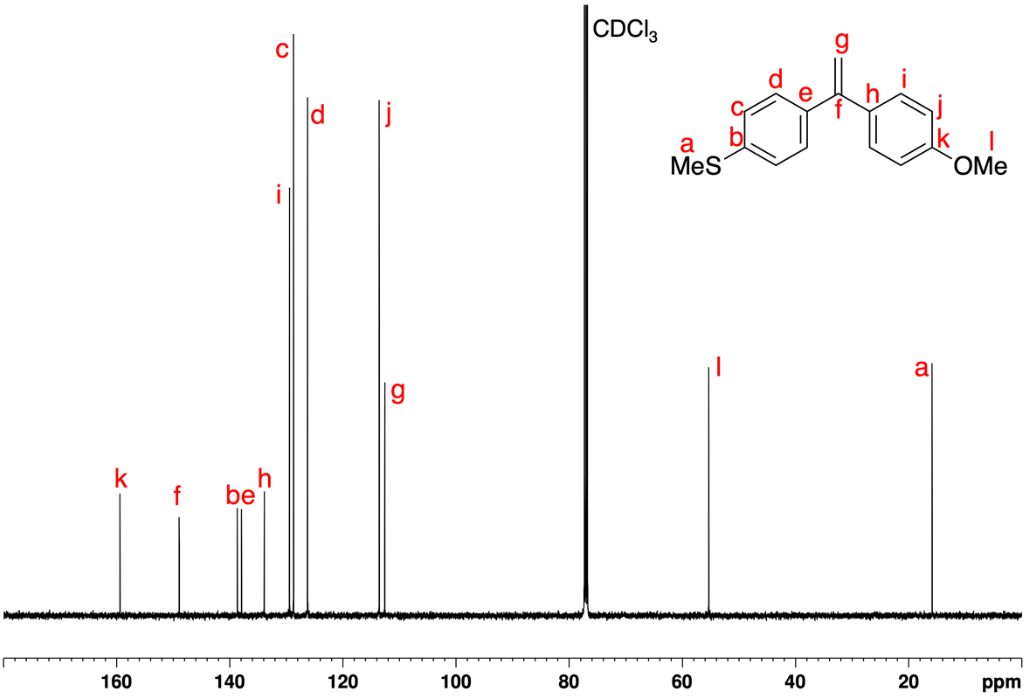

Figure S6. ^{13}C NMR spectrum of **DAE-SMe/OMe** ($CDCl_3$, 125 MHz).

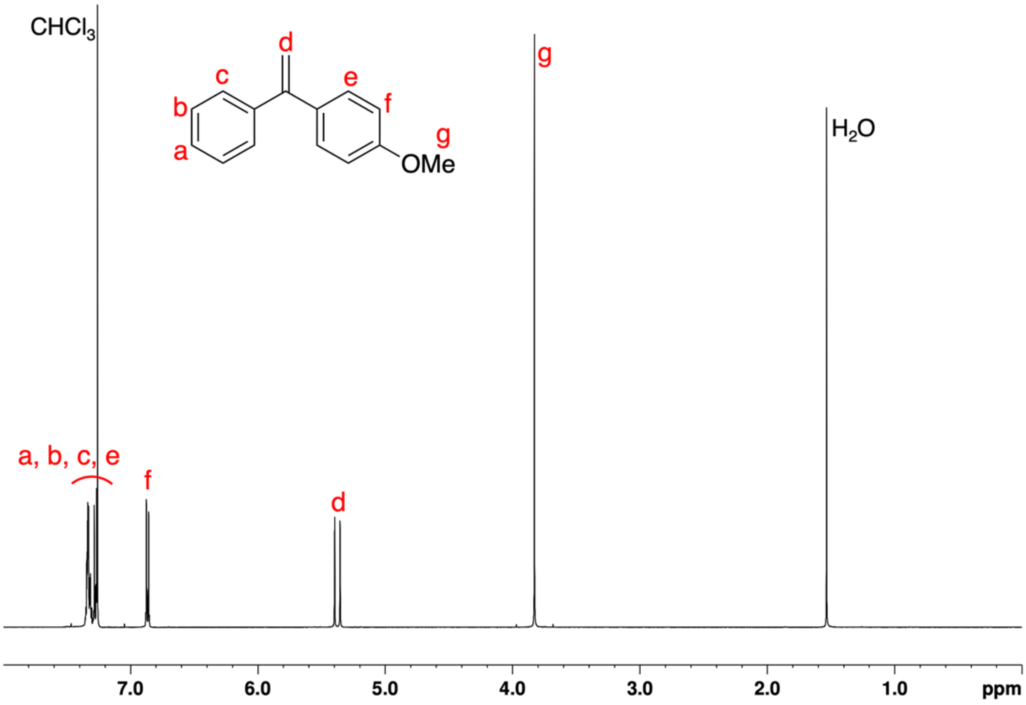

Figure S7. ^{1}H NMR spectrum of **DAE-H/OMe** ($CDCl_3$, 500 MHz).

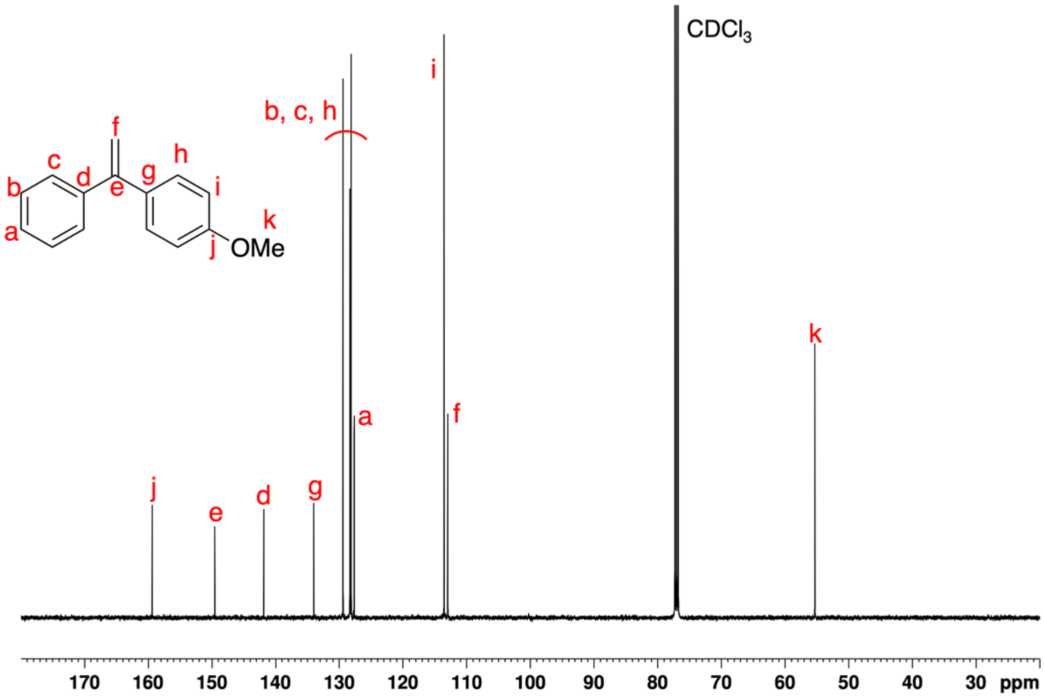

Figure S8. ^{13}C NMR spectrum of **DAE-H/OMe** ($CDCl_3$, 125 MHz).

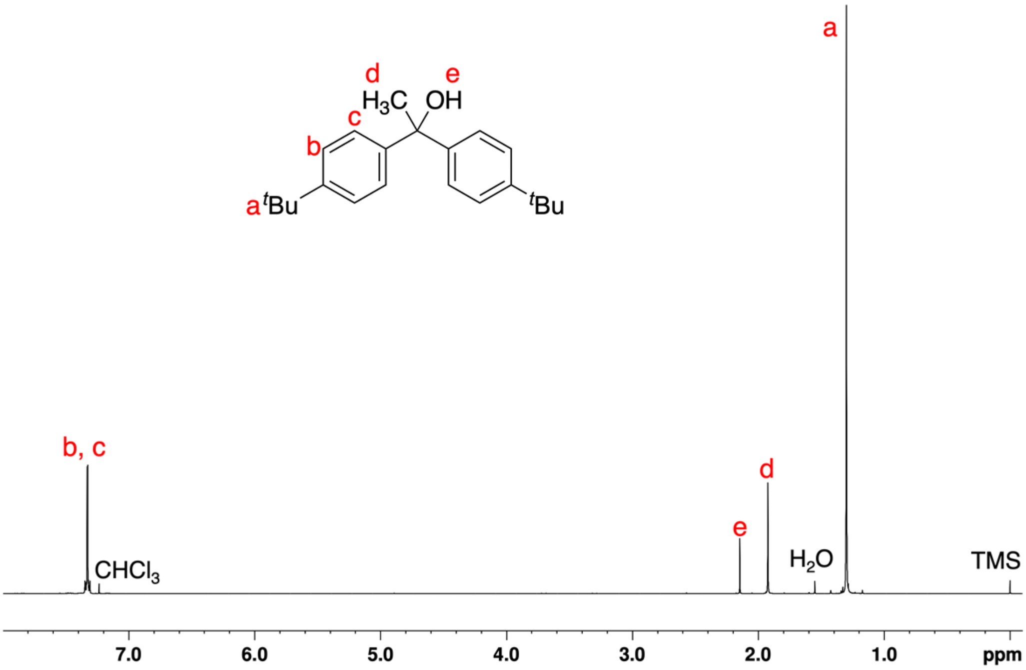

Figure S9. ^{1}H NMR spectrum of compound **2** ($CDCl_3$, 500 MHz).

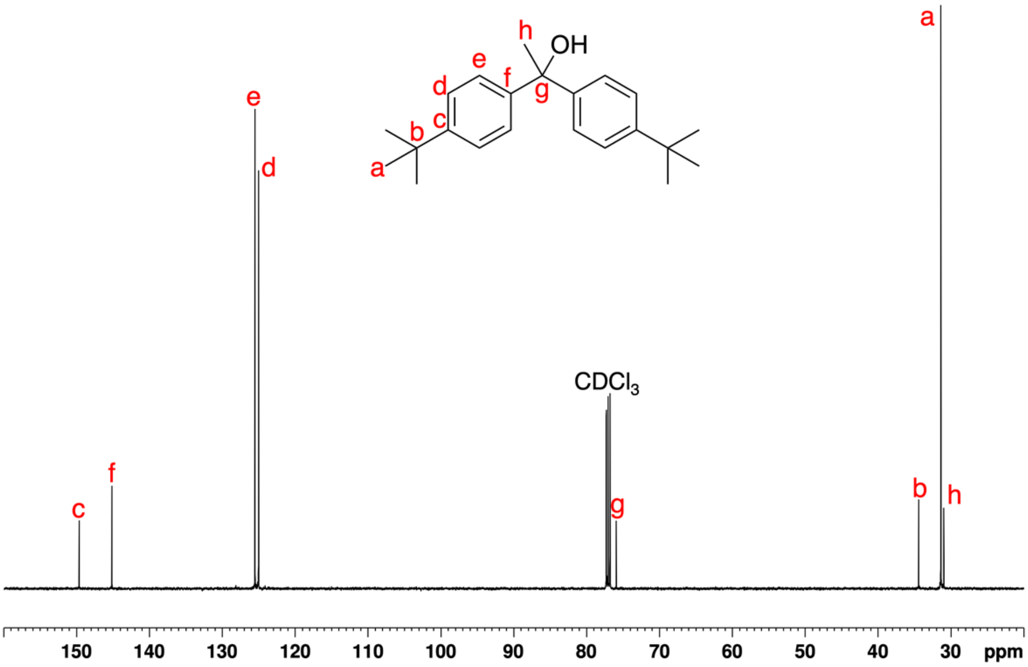

Figure S10. ^{13}C NMR spectrum of compound **2** ($CDCl_3$, 125 MHz).

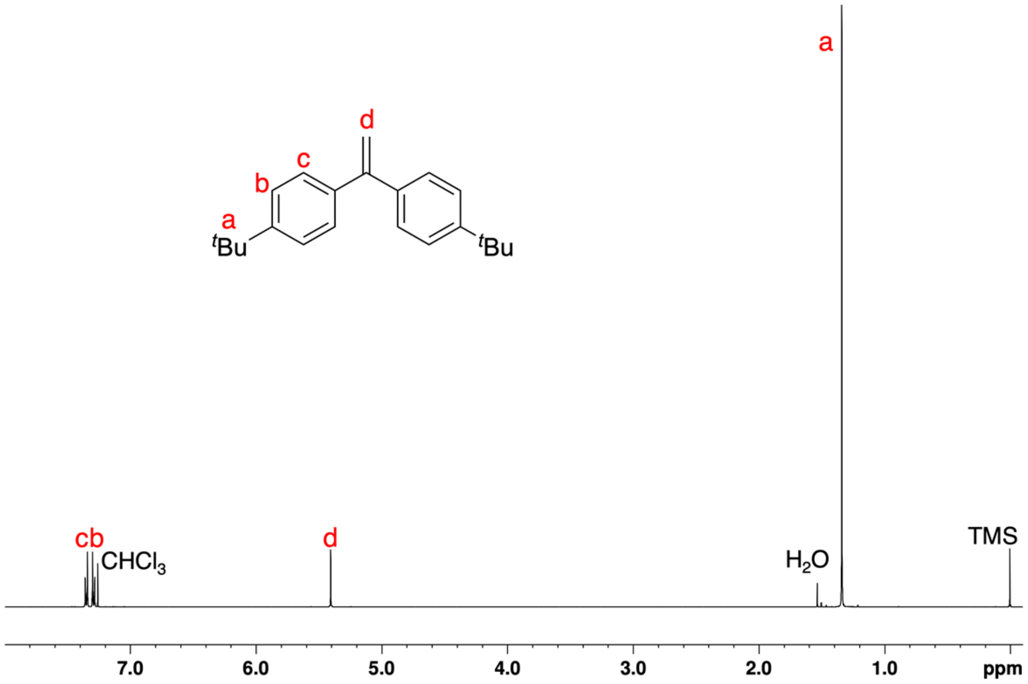

Figure S11. ^{1}H NMR spectrum of **DAE-^{t}Bu/^{t}Bu** (CDCl$_3$, 500 MHz).

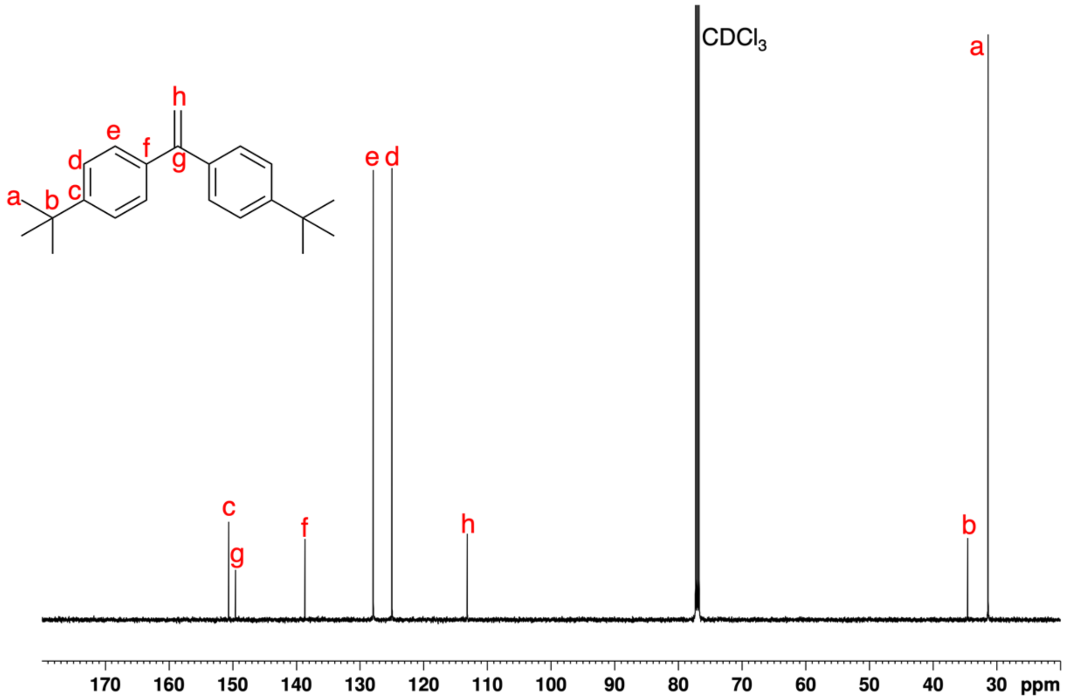

Figure S12. ^{13}C NMR spectrum of **DAE-^{t}Bu/^{t}Bu** (CDCl$_3$, 125 MHz).

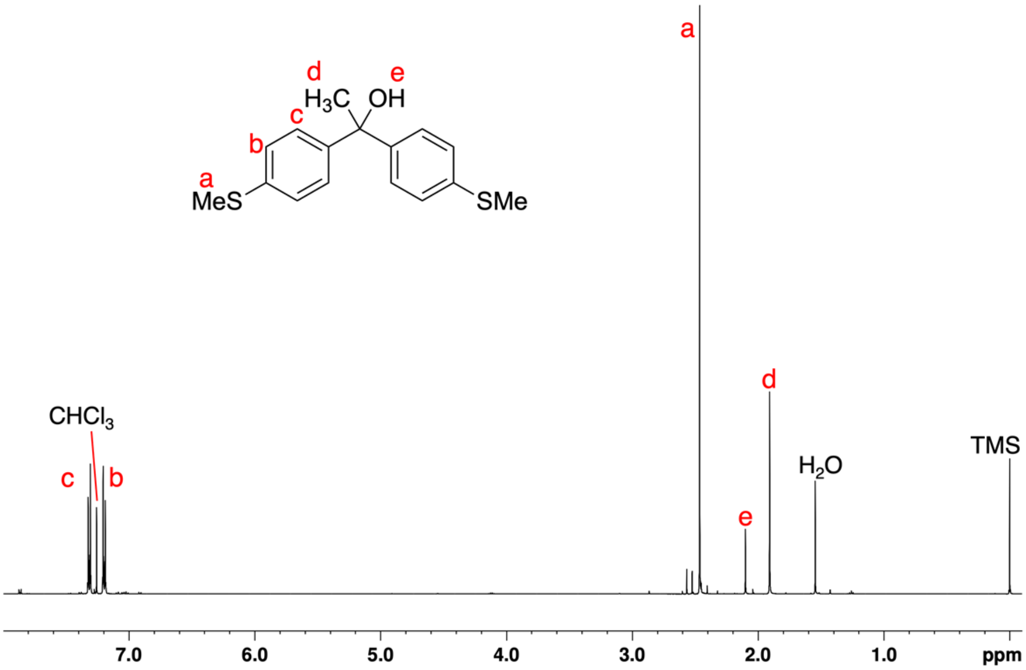

Figure S13. ^{1}H NMR spectrum of compound **3** ($CDCl_3$, 500 MHz).

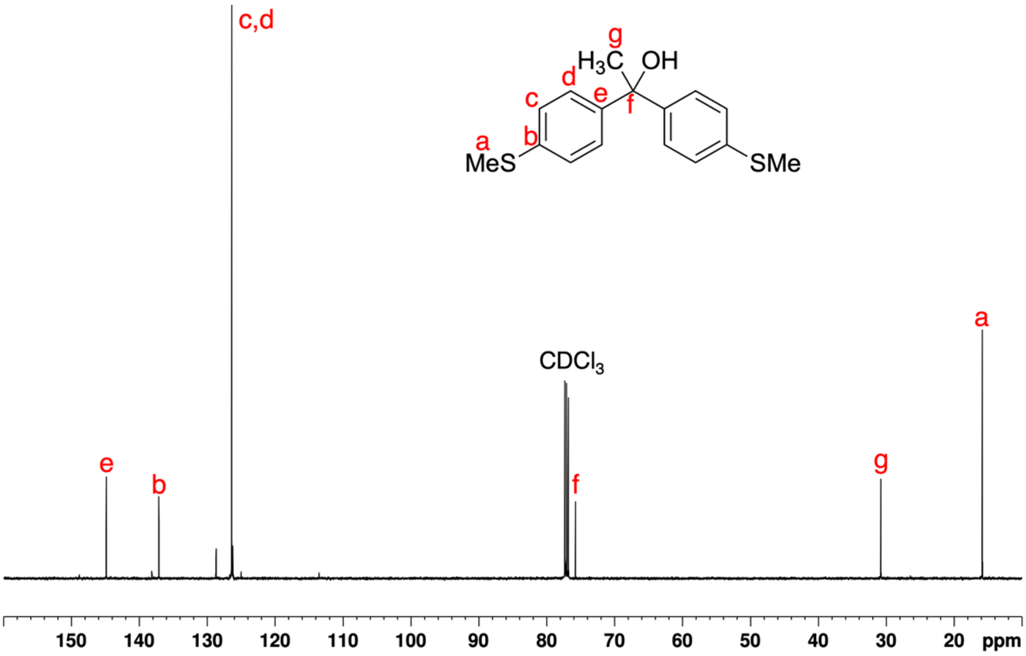

Figure S14. ^{13}C NMR spectrum of compound **3** ($CDCl_3$, 125 MHz).

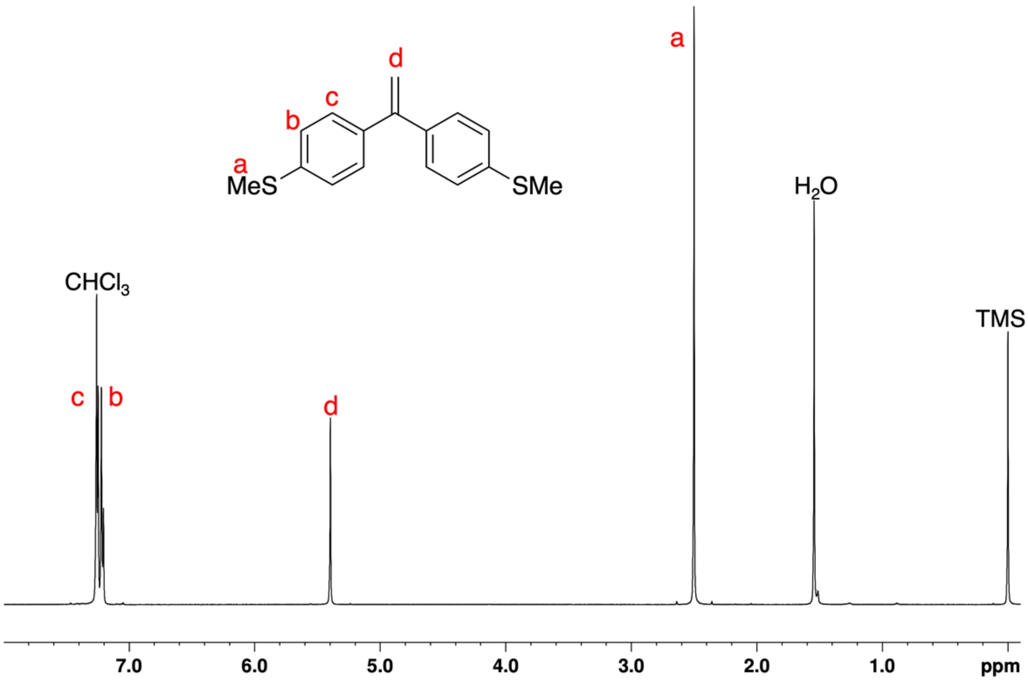

Figure S15. ^{1}H NMR spectrum of **DAE-SMe/SMe** ($CDCl_3$, 500 MHz).

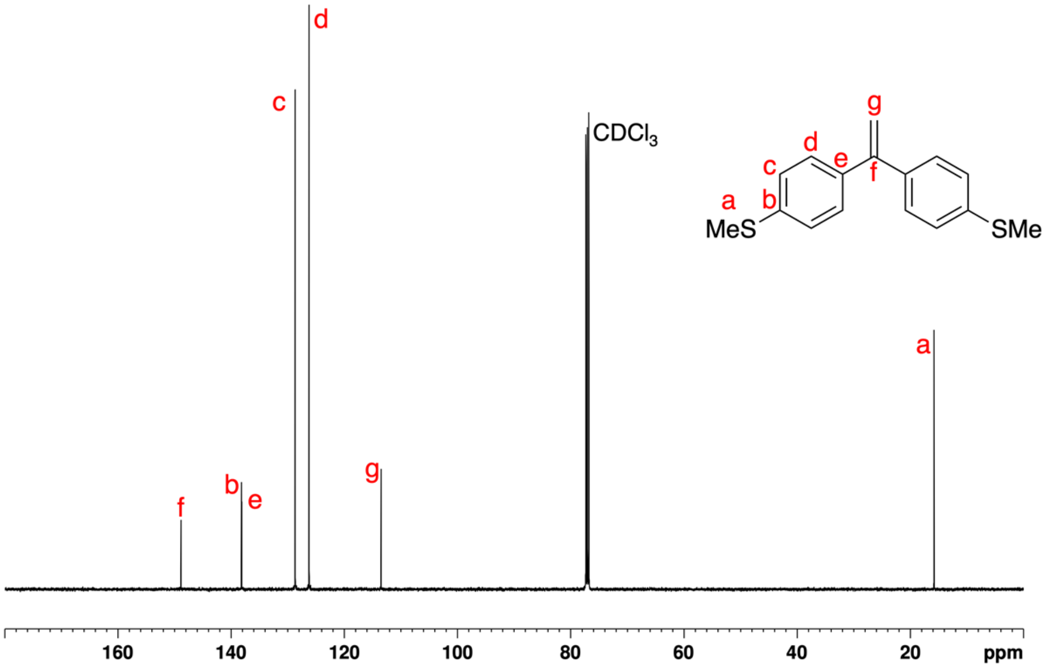

Figure S16. ^{13}C NMR spectrum of **DAE-^{t}Bu/^{t}Bu** ($CDCl_3$, 125 MHz).

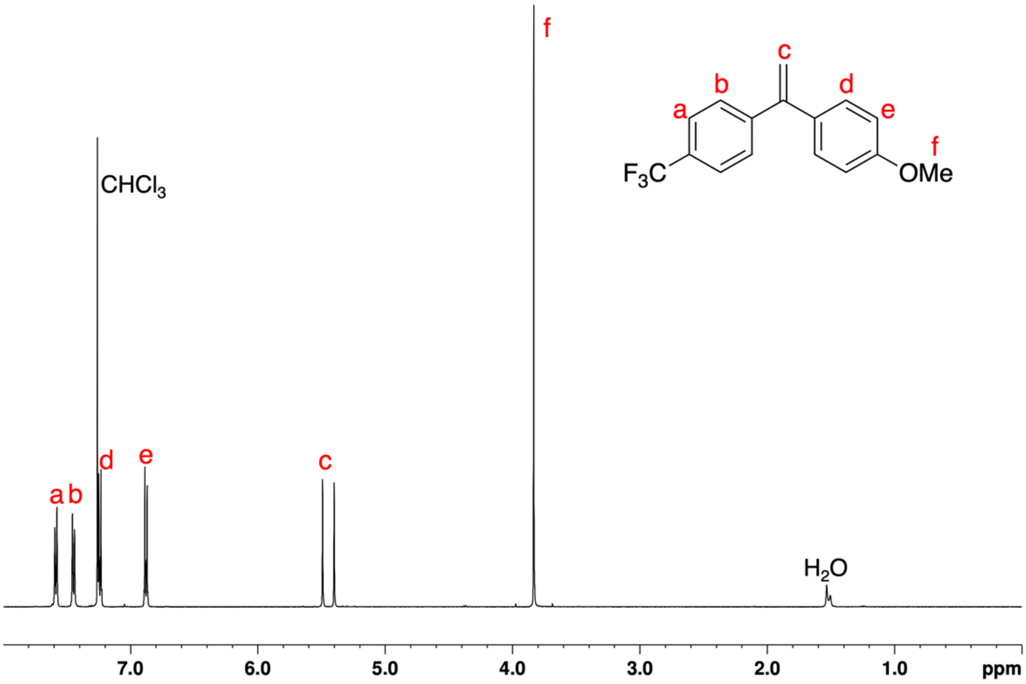

Figure S17. ^1H NMR spectrum of **DAE-CF_3/OMe** ($CDCl_3$, 500 MHz).

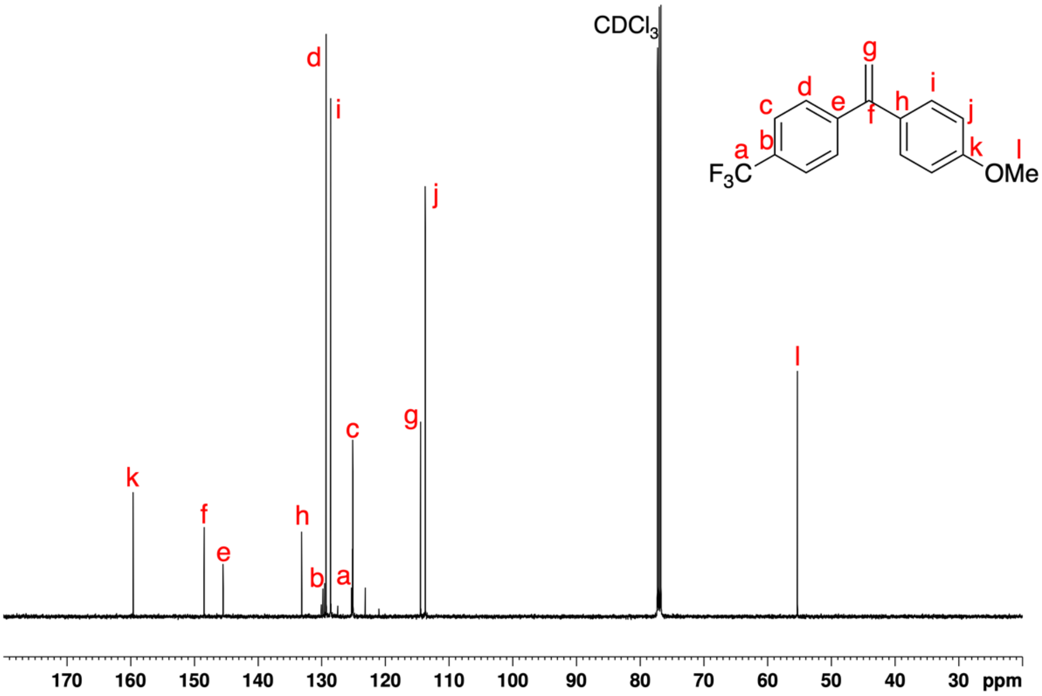

Figure S18. ^{13}C NMR spectrum of **DAE-CF_3/OMe** ($CDCl_3$, 125 MHz).

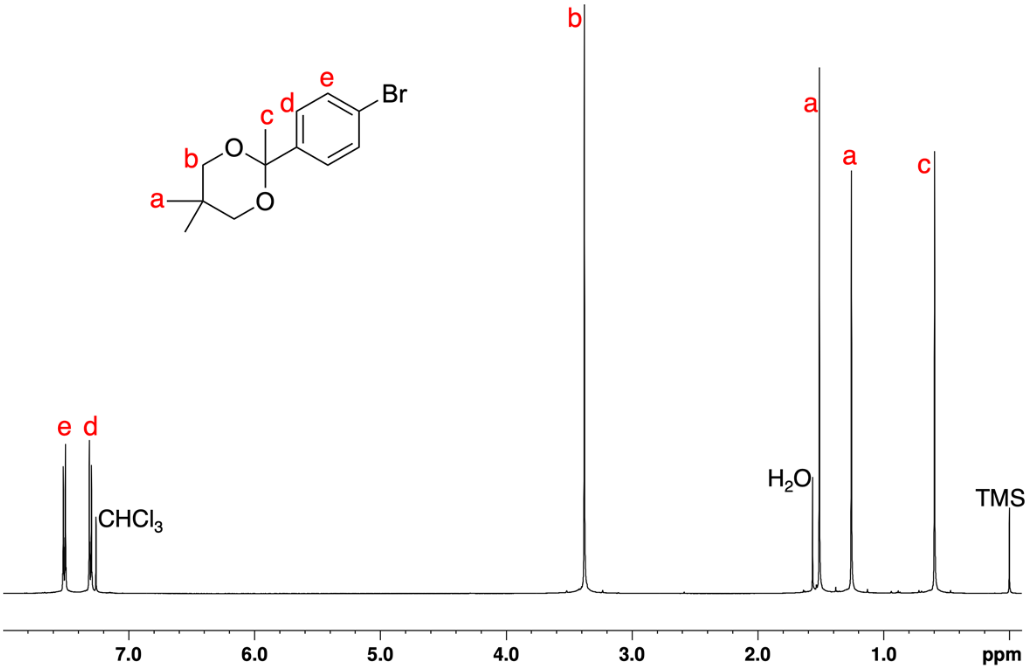

Figure S19. ^{1}H NMR spectrum of compound **4** ($CDCl_3$, 500 MHz).

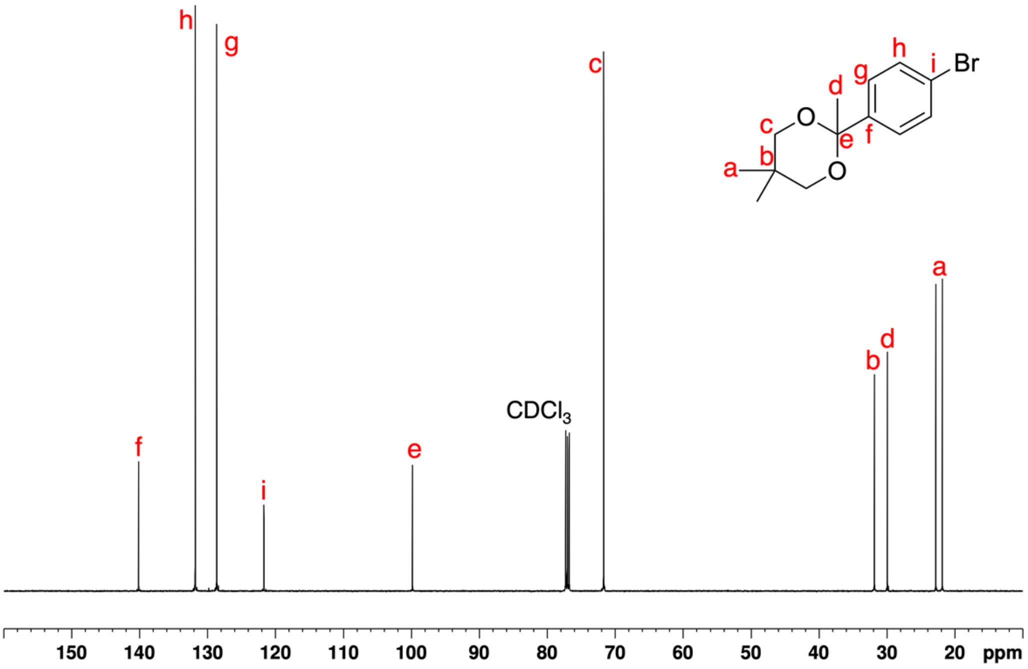

Figure S20. ^{13}C NMR spectrum of compound **4** ($CDCl_3$, 125 MHz).

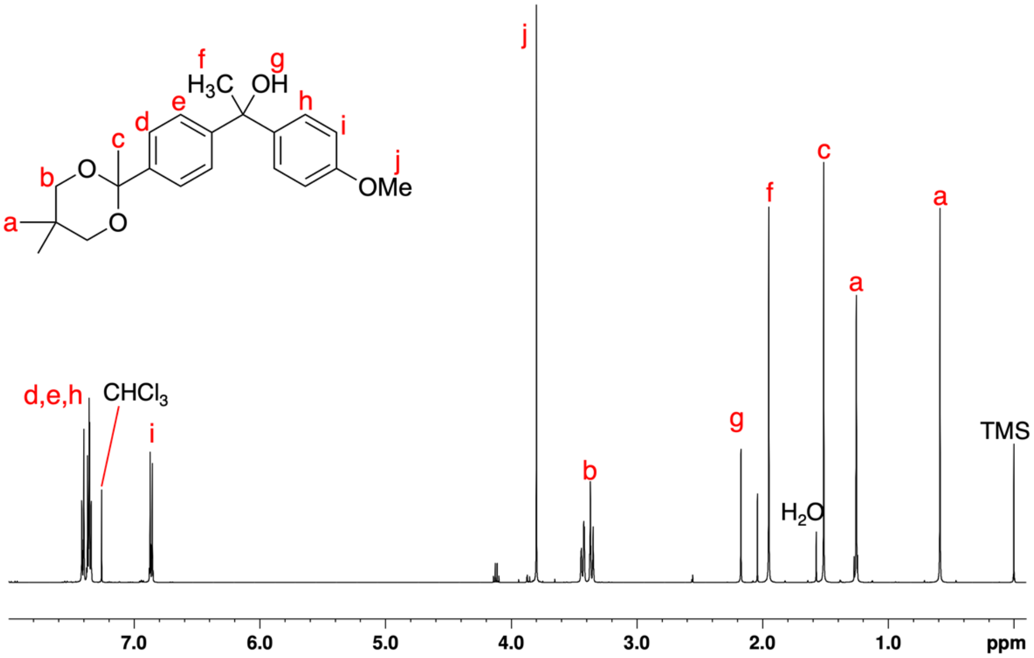

Figure S21. ^{1}H NMR spectrum of compound **5** ($CDCl_3$, 500 MHz).

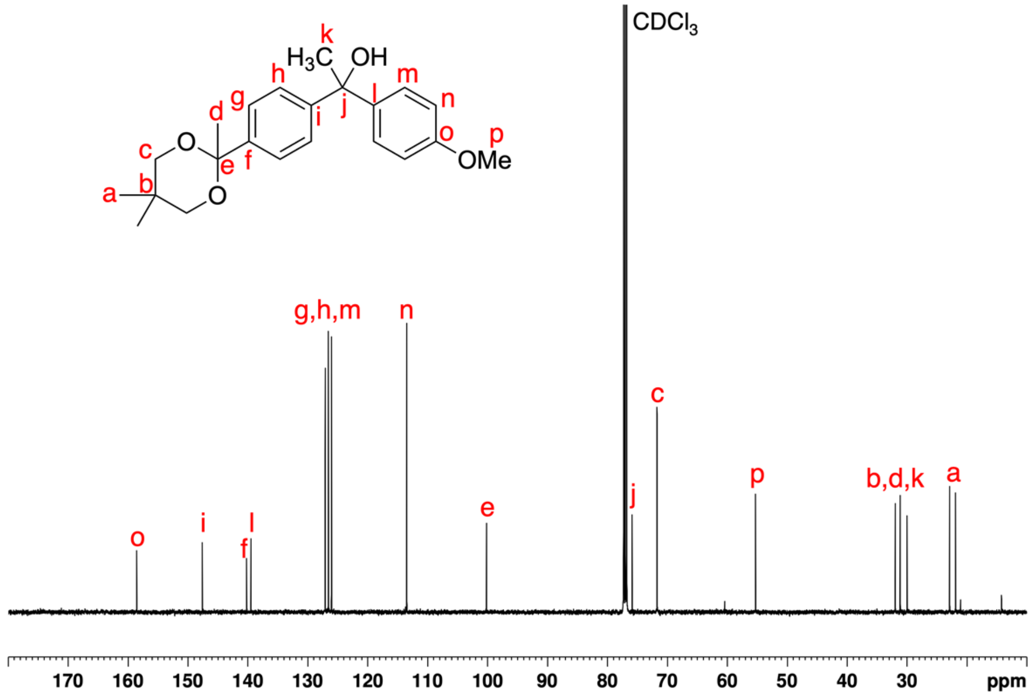

Figure S22. ^{13}C NMR spectrum of compound **5** ($CDCl_3$, 125 MHz).

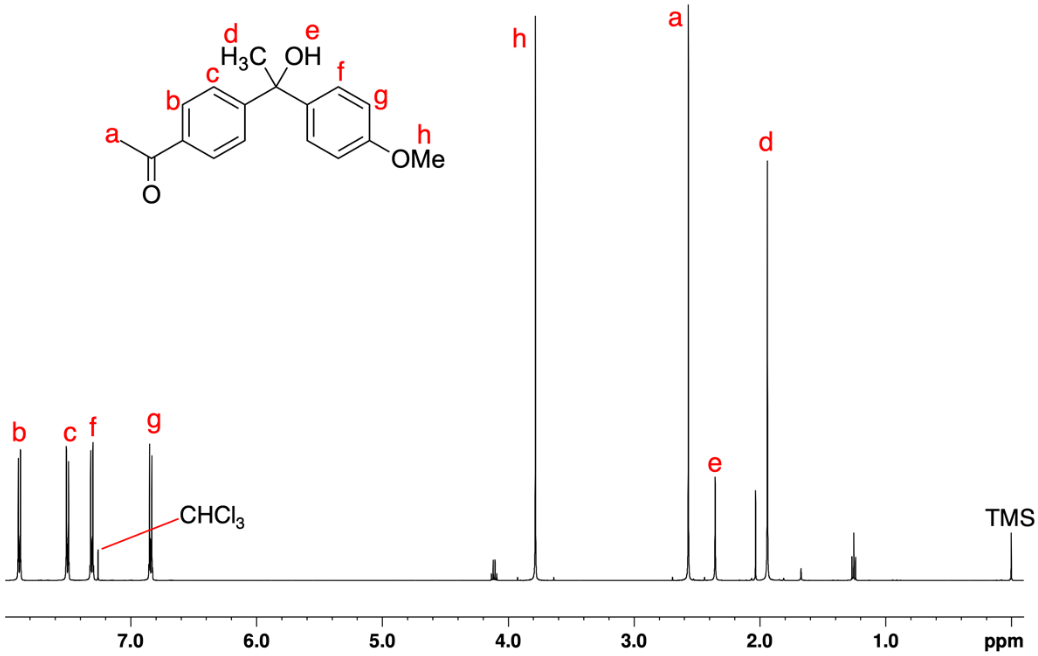

Figure S23. ^1H NMR spectrum of compound **6** ($CDCl_3$, 500 MHz).

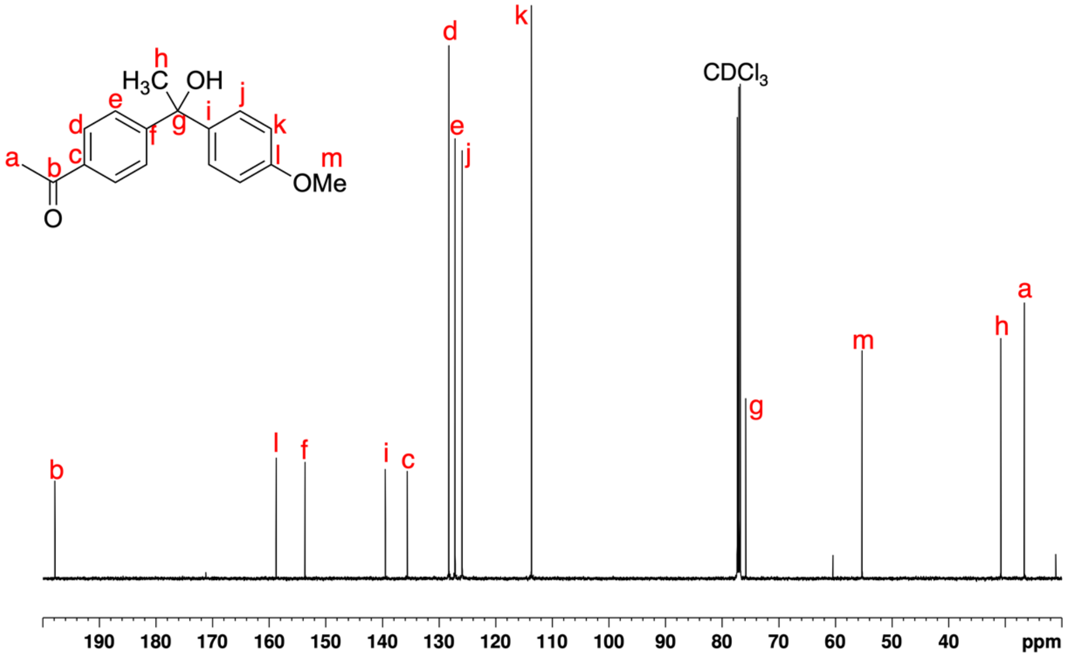

Figure S24. ^{13}C NMR spectrum of compound **6** ($CDCl_3$, 125 MHz).

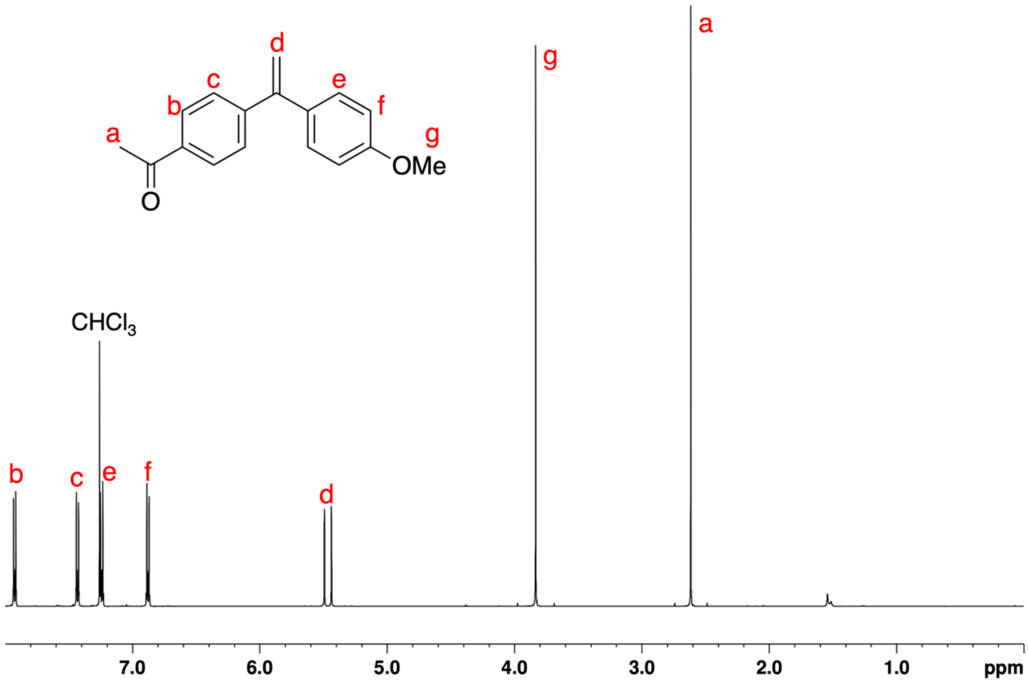

Figure S25. ^{1}H NMR spectrum of **DAE-Ac/OMe** (CDCl$_3$, 500 MHz).

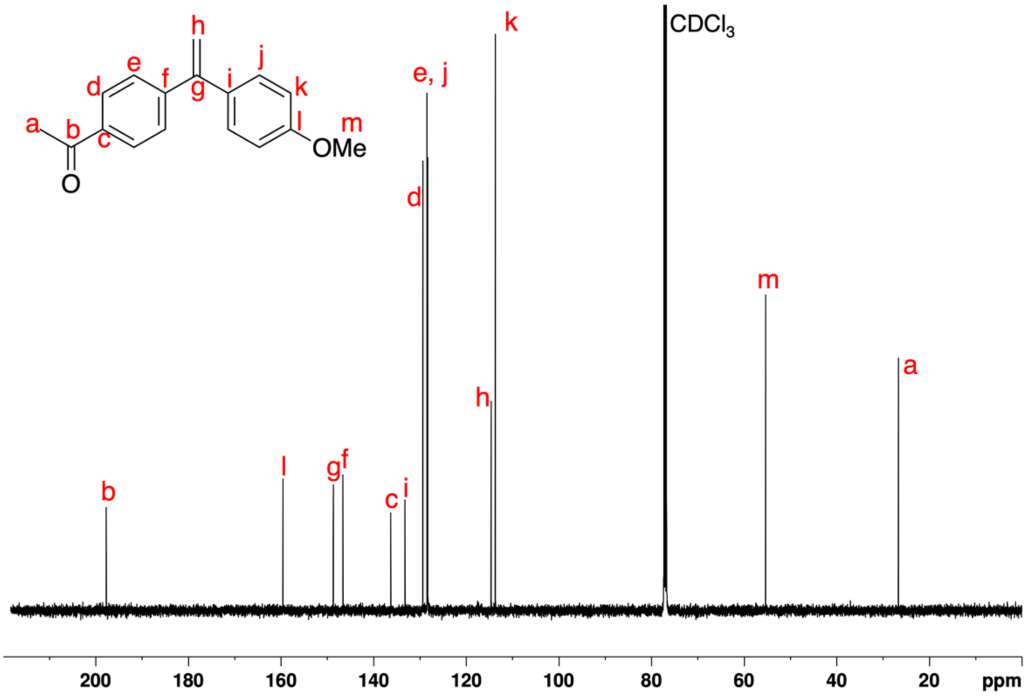

Figure S26. ^{13}C NMR spectrum of **DAE-Ac/OMe** (CDCl$_3$, 125 MHz).

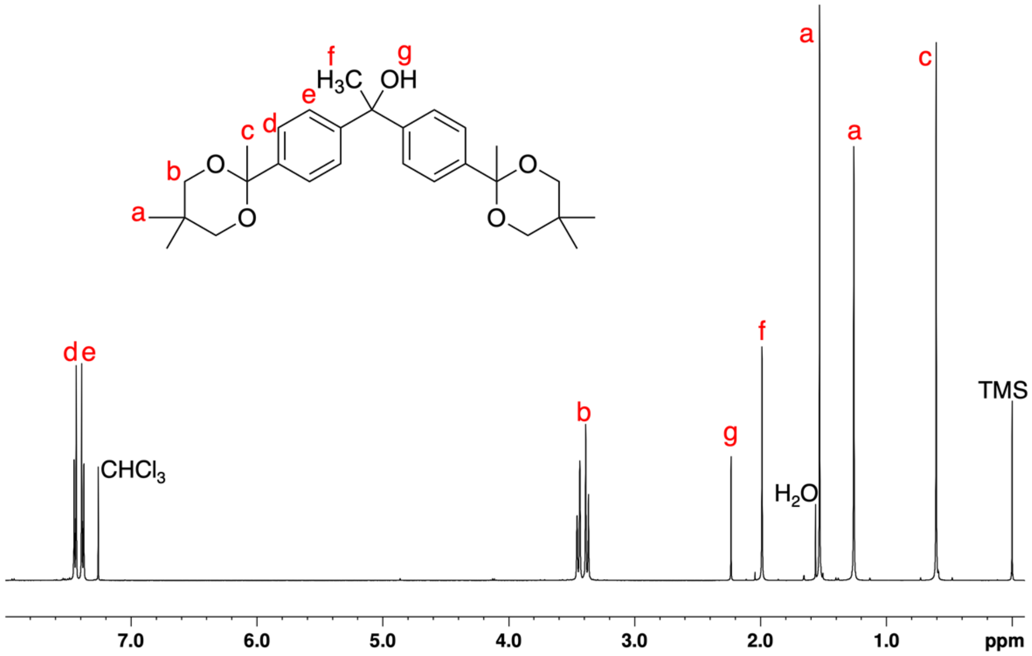

Figure S27. ^1H NMR spectrum of compound **7** ($CDCl_3$, 500 MHz).

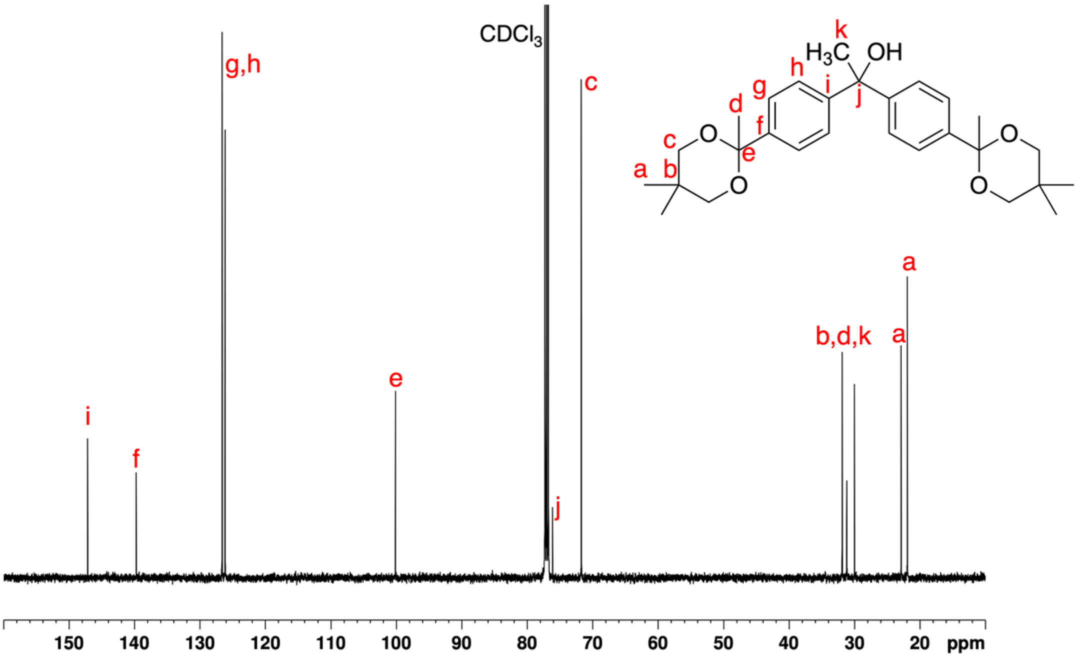

Figure S28. ^{13}C NMR spectrum of compound **7** ($CDCl_3$, 125 MHz).

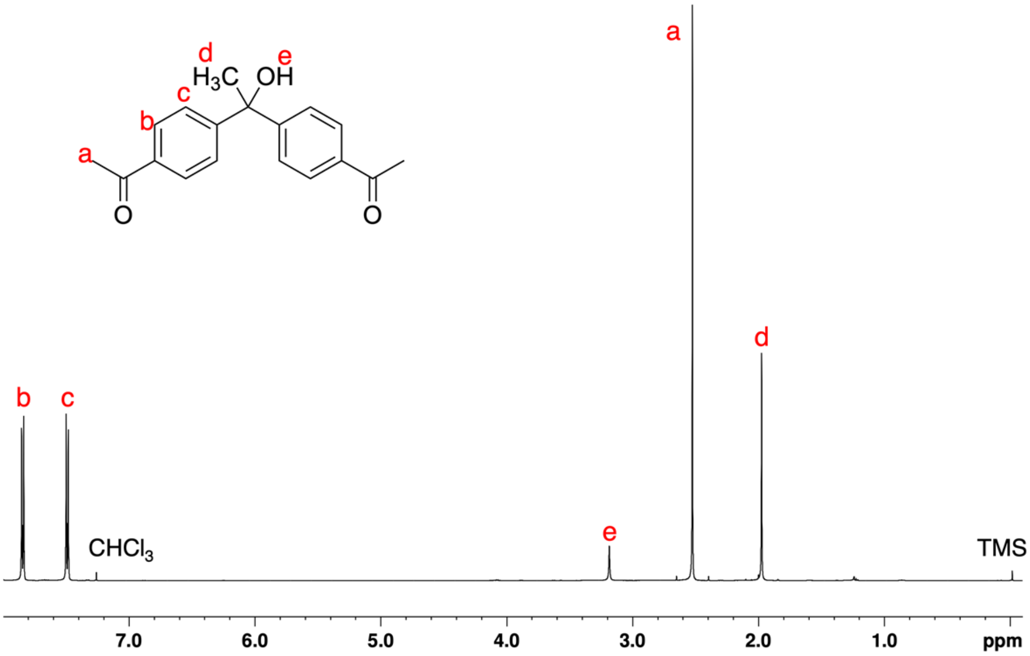

Figure S29. ^{1}H NMR spectrum of compound **8** ($CDCl_3$, 500 MHz).

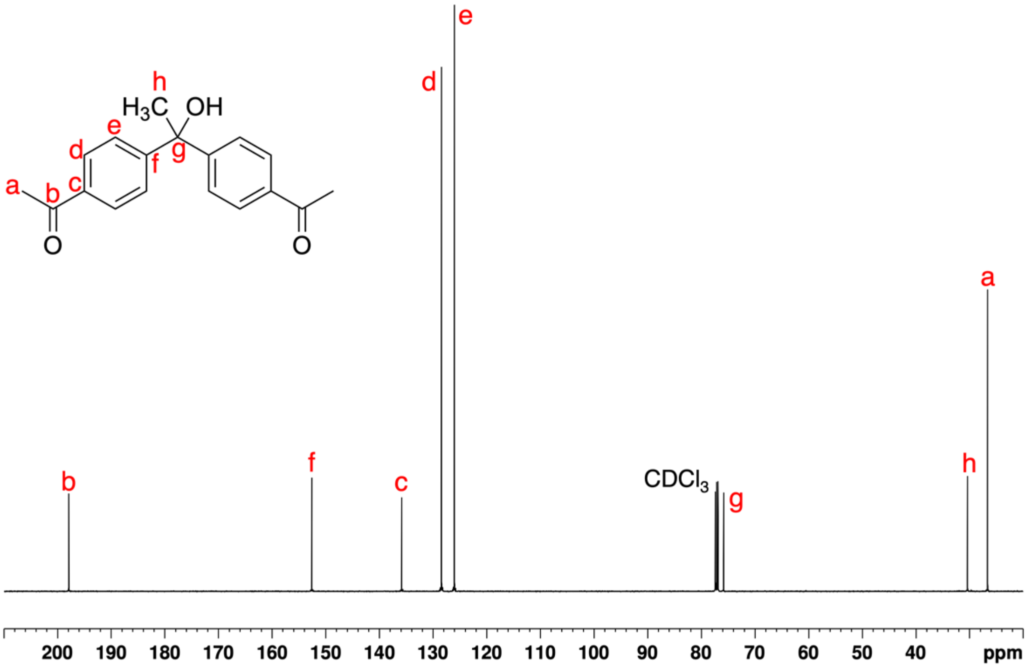

Figure S30. ^{13}C NMR spectrum of compound **8** ($CDCl_3$, 125 MHz).

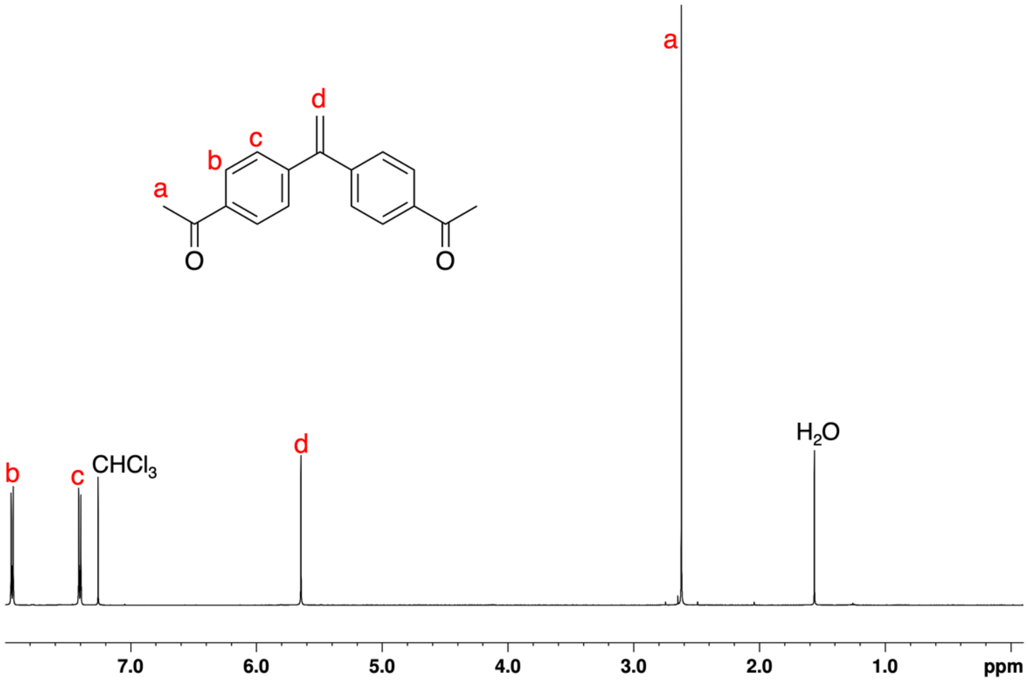

Figure S31. ^{1}H NMR spectrum of **DAE-Ac/Ac** ($CDCl_3$, 500 MHz).

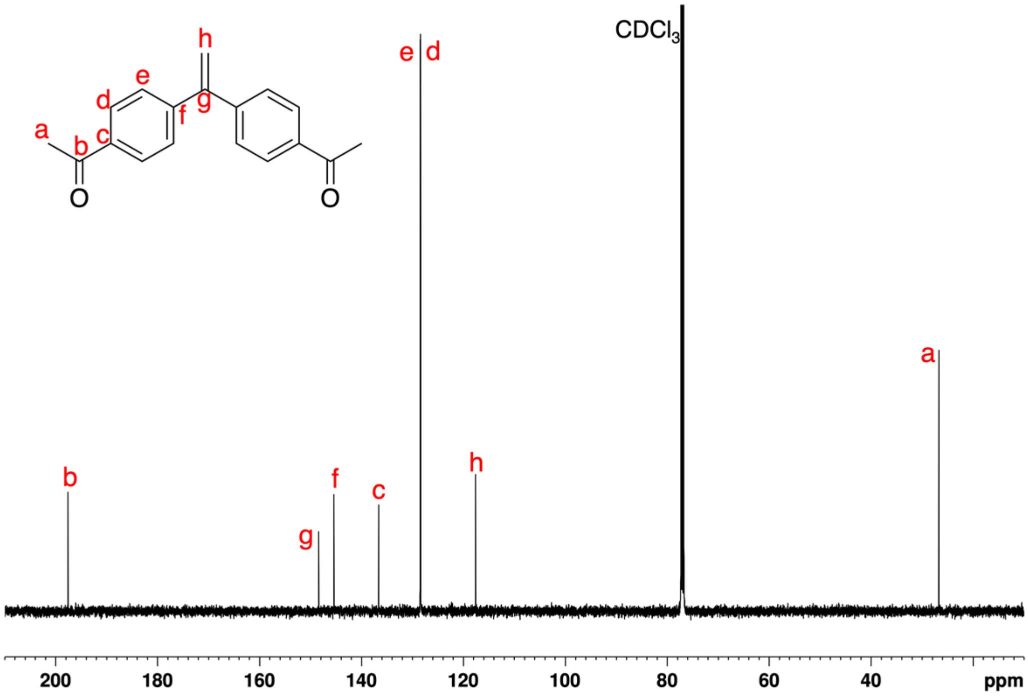

Figure S32. ^{13}C NMR spectrum of **DAE-Ac/Ac** ($CDCl_3$, 125 MHz).

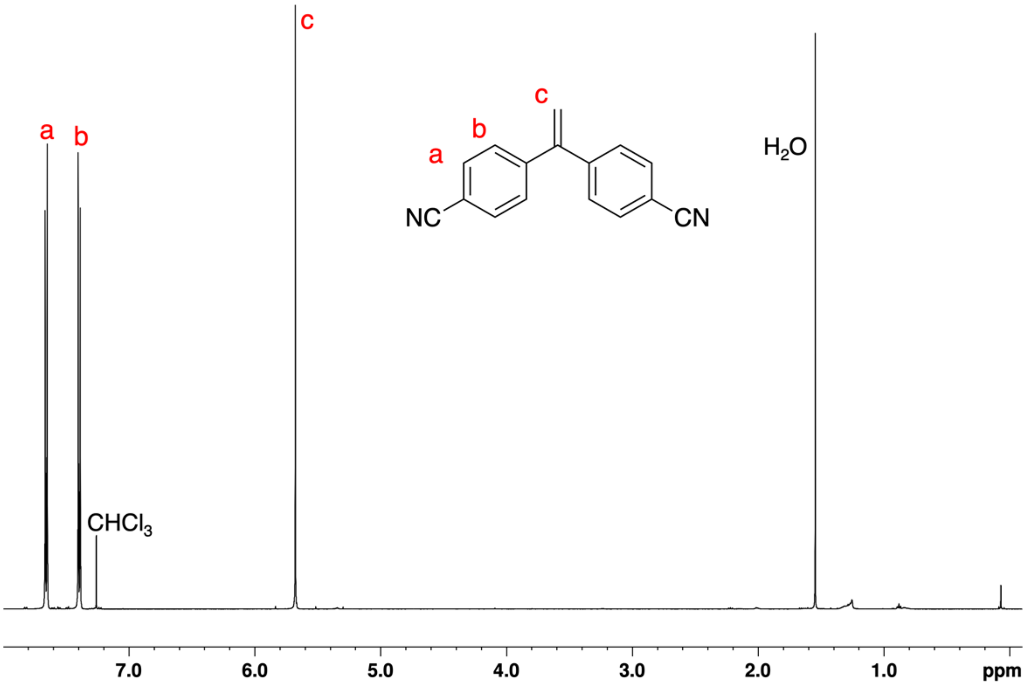

Figure S33. ^{1}H NMR spectrum of **DAE-CN/CN** (CDCl$_3$, 500 MHz).

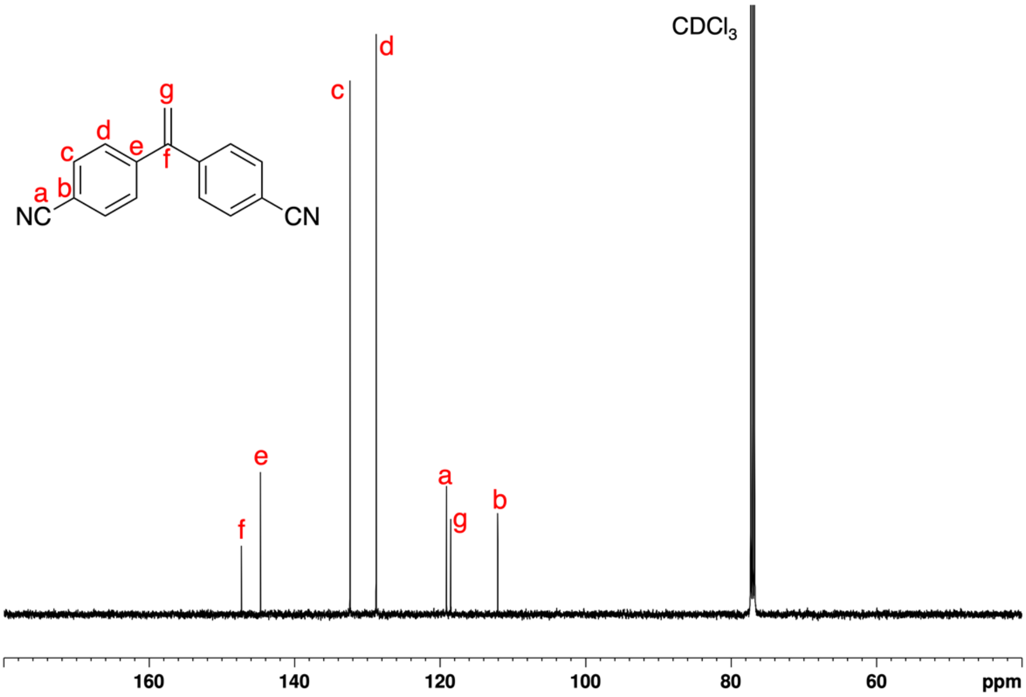

Figure S34. ^{13}C NMR spectrum of **DAE-CN/CN** (CDCl$_3$, 125 MHz).

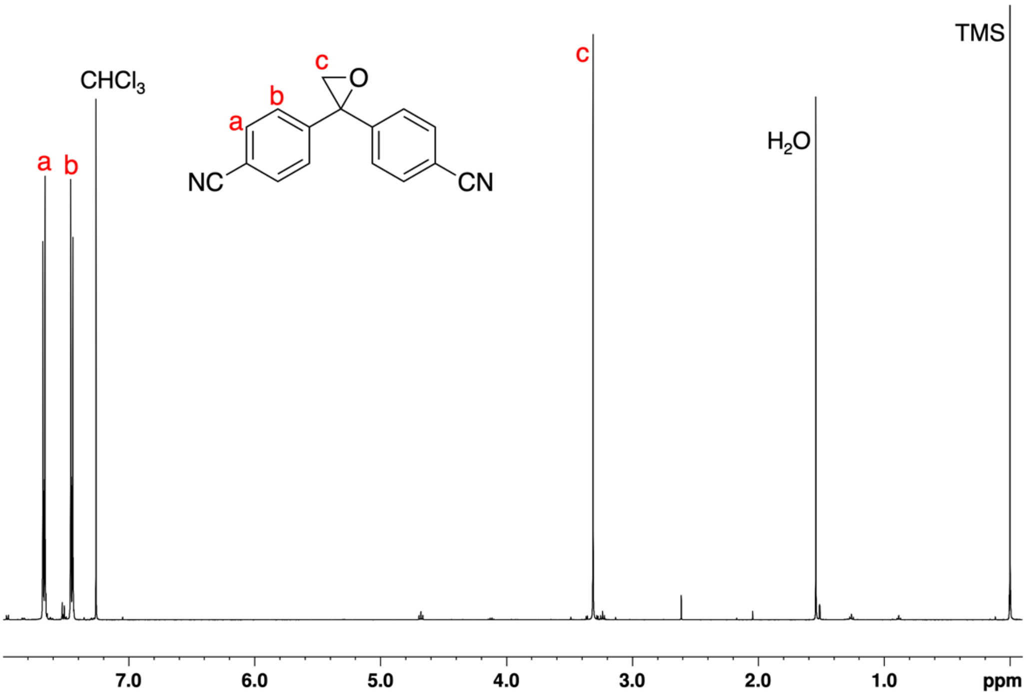

Figure S35. ^{1}H NMR spectrum of **DAO-CN/CN** ($CDCl_3$, 500 MHz).

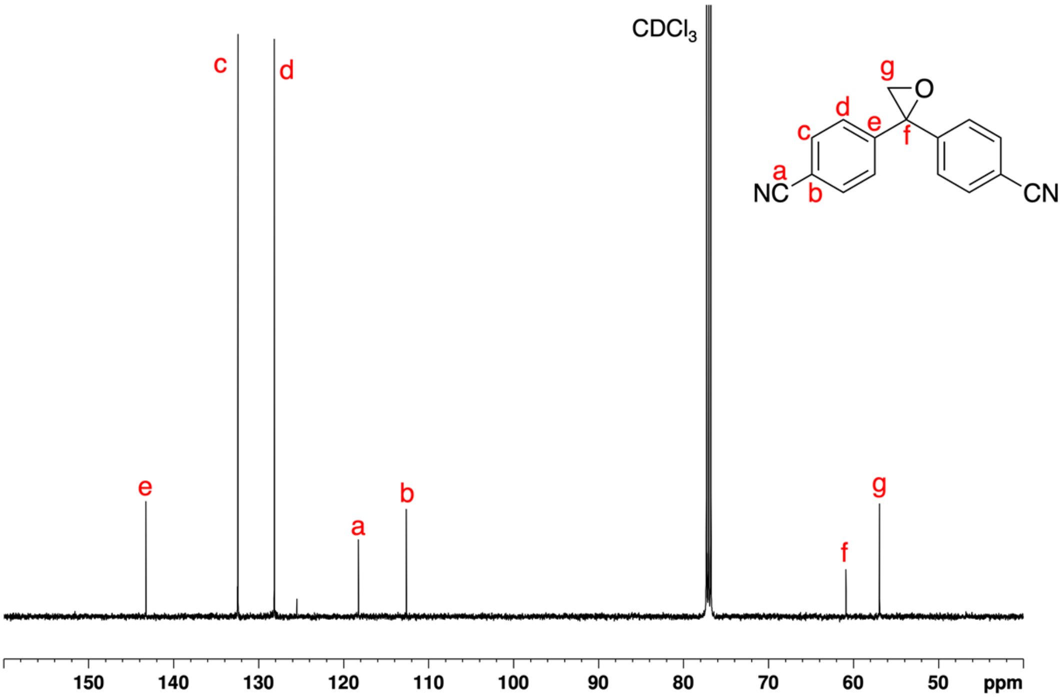

Figure S36. ^{13}C NMR spectrum of **DAO-CN/CN** ($CDCl_3$, 125 MHz).

4. Experimental Procedure

4.1 Ball-milling tests

Ball-milling tests were performed using a mixer mill (Retsch MM 400). The mechanical energy was controlled by the oscillation frequency of the screw-cap jar. The powdered sample was placed in a 10 mL stainless steel screw-cap jar containing one 5 mm stainless steel ball. The jar was sealed and mounted in the mill. The samples were ground at 30 Hz for 60 min under air ambient laboratory conditions. The temperature of the sample immediately after milling was not directly measured in the present study.

Ball milling of a mixture of polymer and small molecule

A polymer (100 mg) and a small molecule (50 μmol) were placed in a ball-mill jar and ground under the conditions described above. Quantitative analysis by ^{1}H NMR spectroscopy was performed by adding an internal standard (1,4-bis(trimethylsilyl)benzene-d_4) to the ground sample, and the conversion of the DAE derivative and the yield of the DAK derivative were determined from the integral ratios of the corresponding signals.

The ^{1}H NMR spectra in the range of 3.0–3.5 ppm, recorded immediately after grinding and after approximately 3 hours, are shown in **Figure S46**.

For purified samples, the ground material was dissolved in chloroform and precipitated with hexane to remove most of the polymer. The diaryl ketone was then isolated by silica gel column chromatography.

For ball-milling experiments under minimized-O_2 conditions, the mixer mill was placed inside a glove bag, which was then purged thoroughly with nitrogen. The oxygen concentration inside the glove bag was monitored with an oxygen meter and reduced to approximately 1.7% before milling. The ball-milling experiments were then carried out inside the glove bag under this nitrogen-enriched atmosphere.

DAE-OMe/OMe

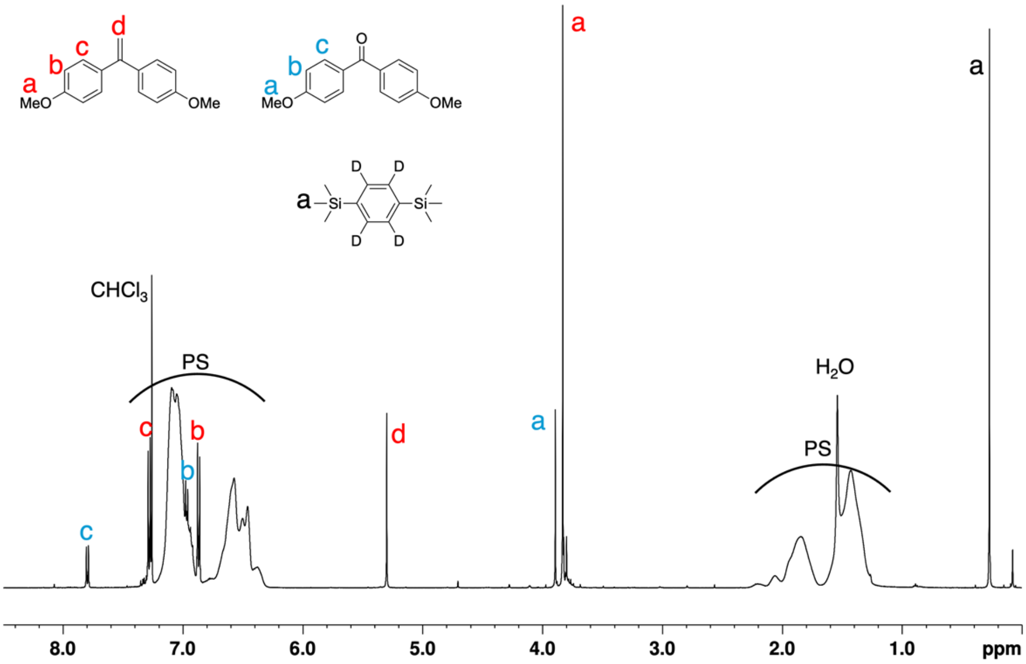

Figure S37. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS after grinding (CDCl$_3$, 500 MHz, Entry 1).

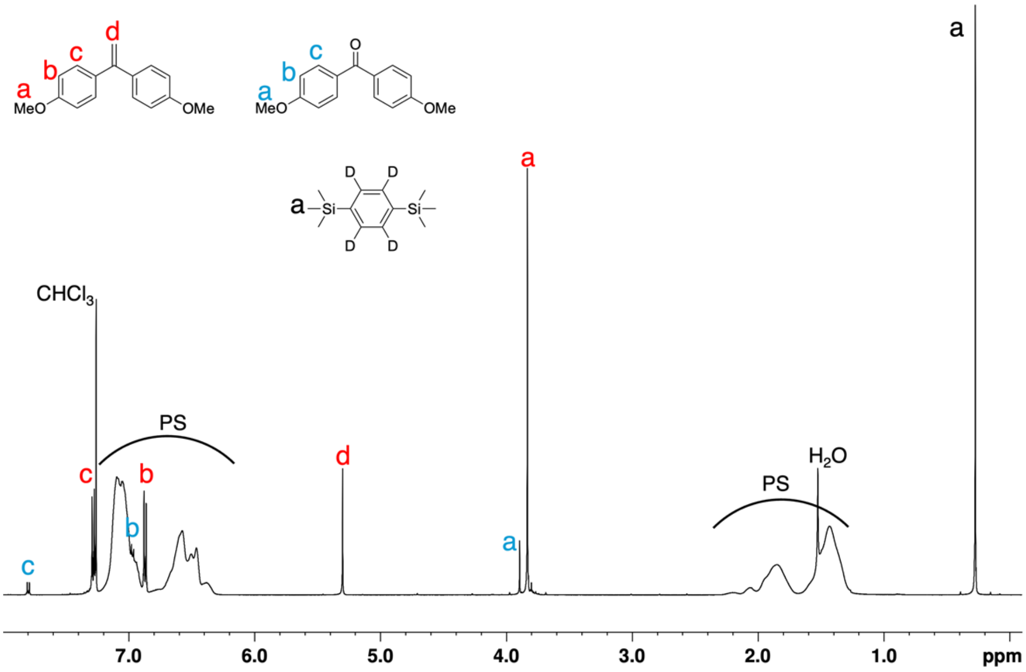

Figure S38. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS after grinding for 30 min (CDCl$_3$, 500 MHz, Entry 2).

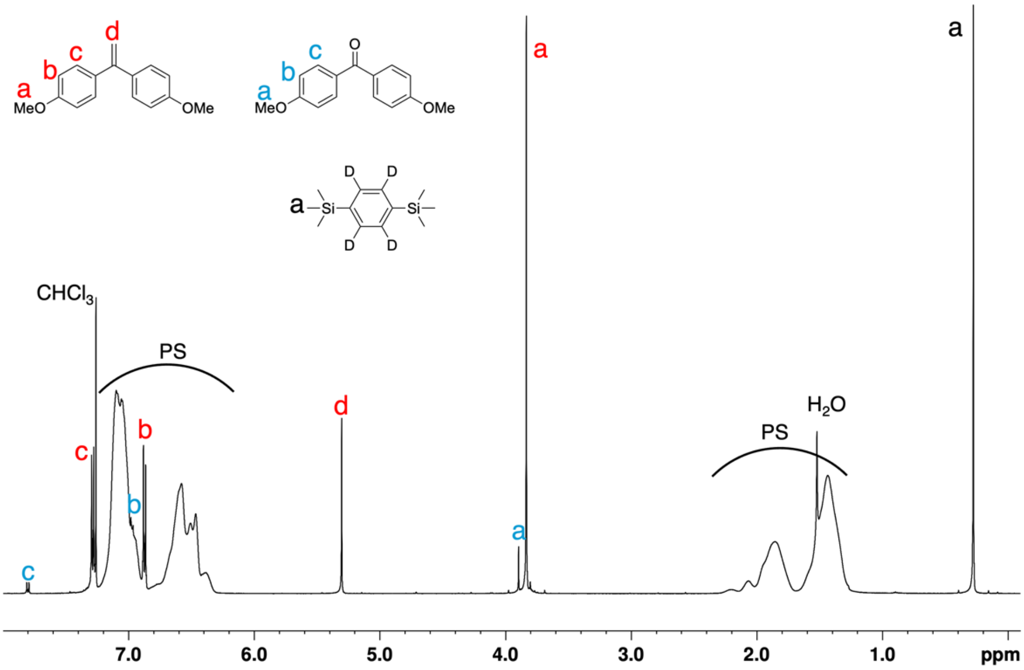

Figure S39. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS after grinding for 15 min (CDCl$_3$, 500 MHz, Entry 3).

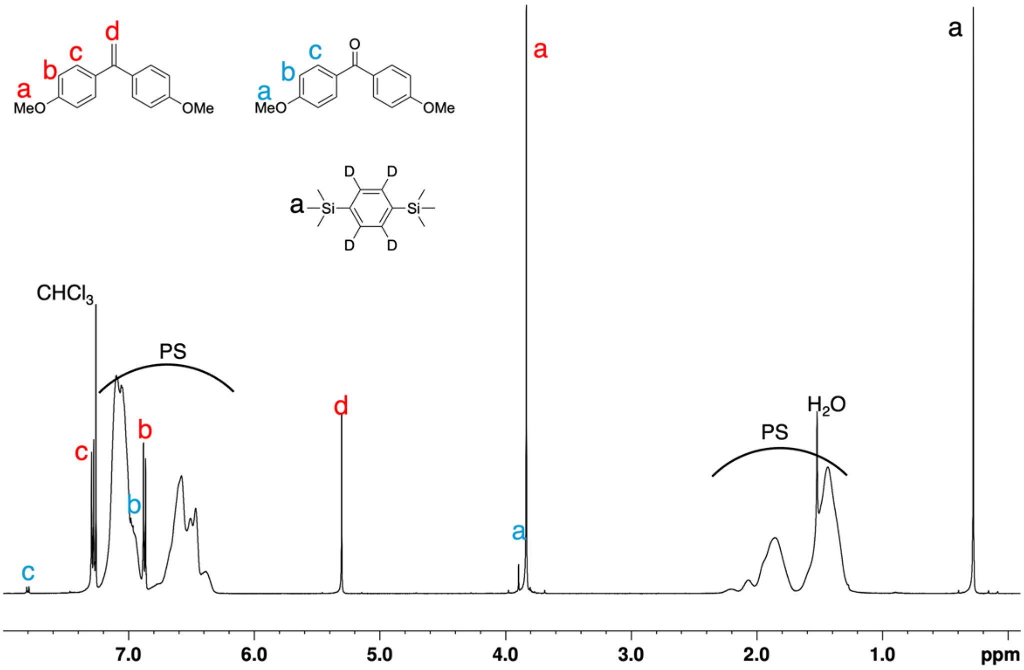

Figure S40. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS after grinding for 10 min (CDCl$_3$, 500 MHz, Entry 4).

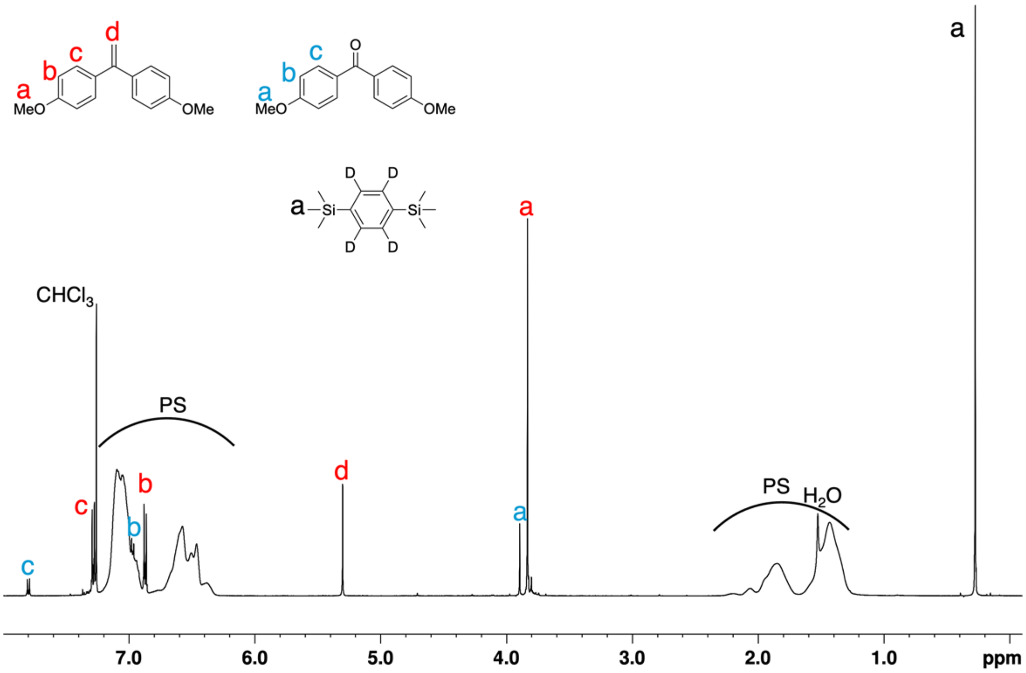

Figure S41. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS (M_n = 792 000) after grinding (CDCl$_3$, 500 MHz, Entry 5).

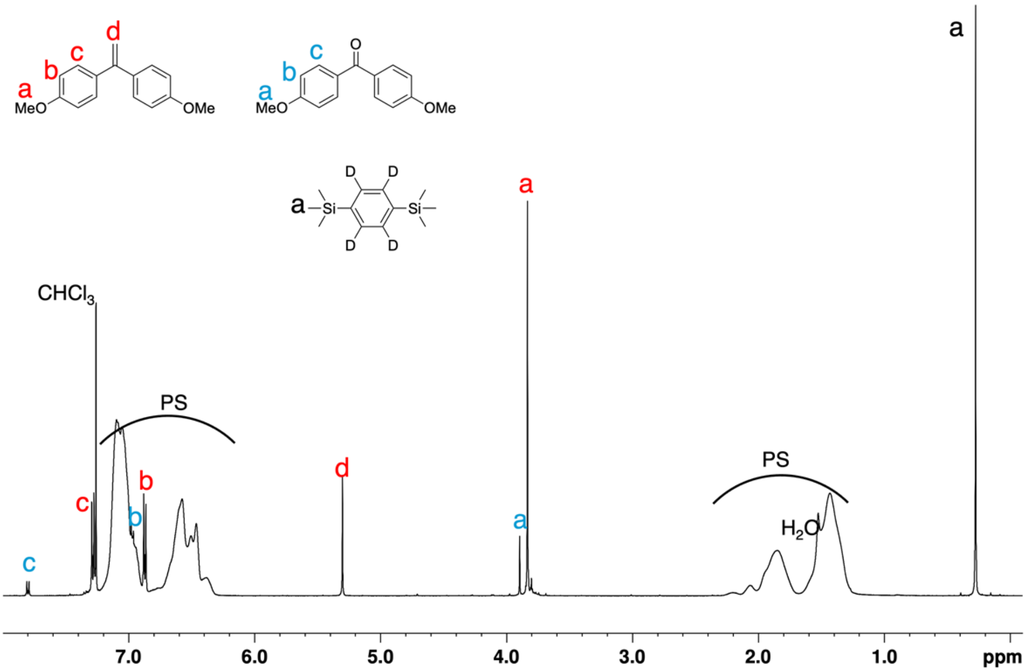

Figure S42. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS (M_n = 320 000) after grinding (CDCl$_3$, 500 MHz, Entry 6).

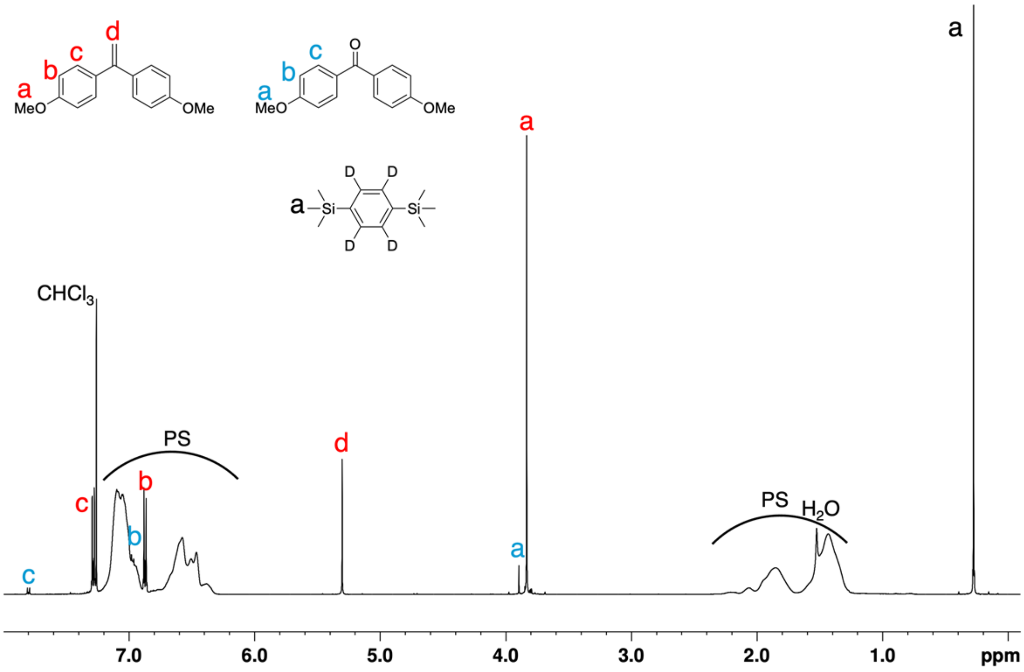

Figure S43. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS (M_n = 38 000) after grinding ($CDCl_3$, 500 MHz, Entry 7).

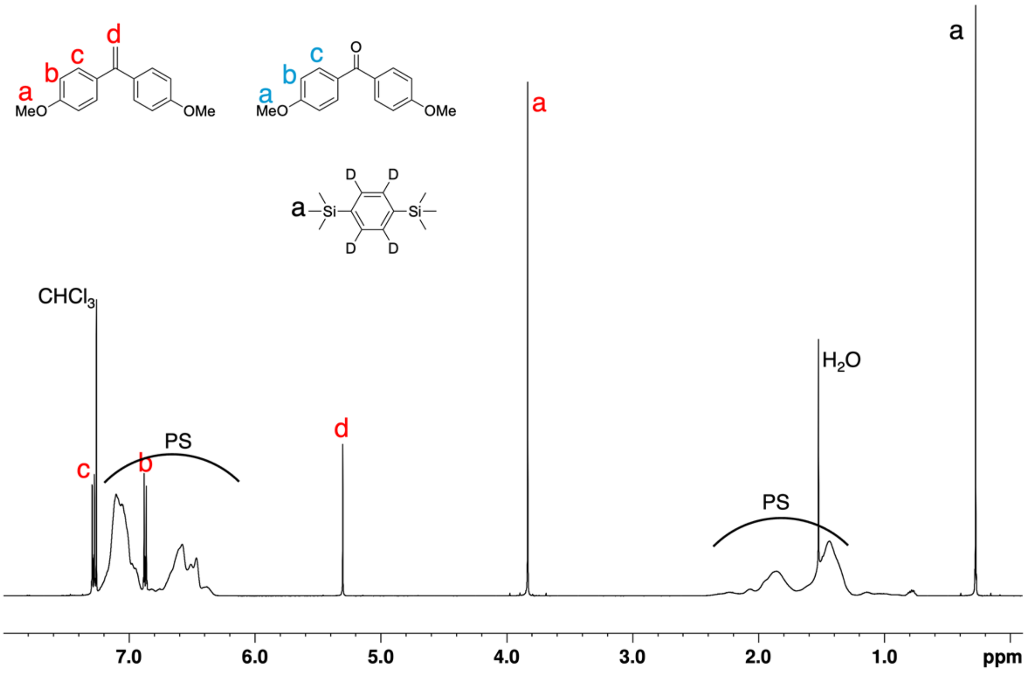

Figure S44. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS (M_n = 6 000) after grinding ($CDCl_3$, 500 MHz, Entry 8).

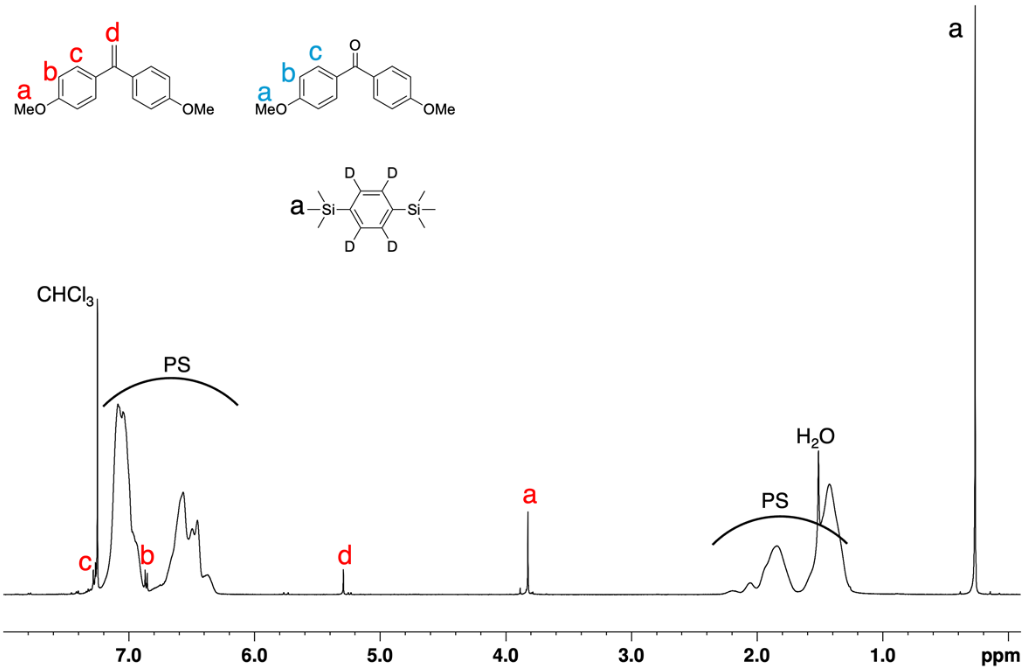

Figure S45. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** (10 μmol) and PS after grinding ($CDCl_3$, 500 MHz, Entry 9).

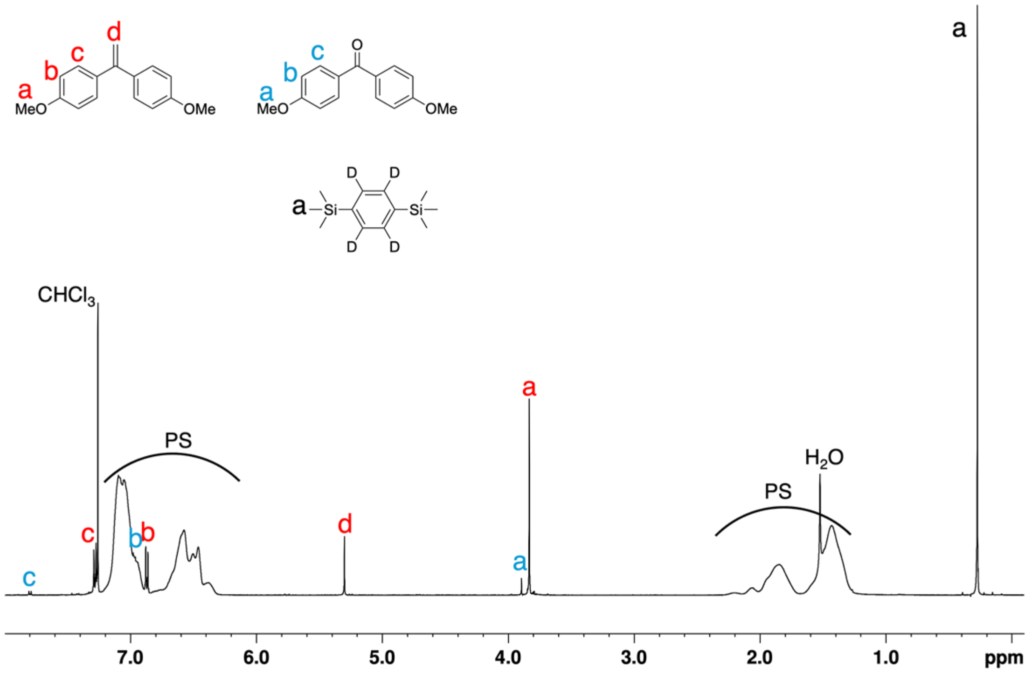

Figure S46. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** (25 μmol) and PS after grinding ($CDCl_3$, 500 MHz, Entry 10).

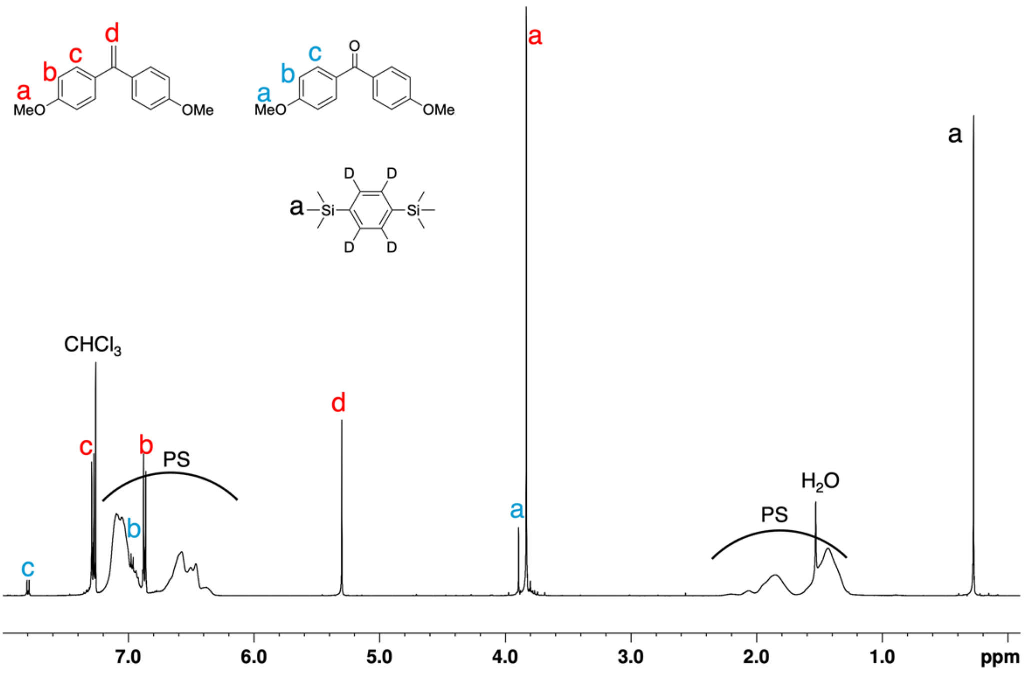

Figure S47. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** (100 µmol) and PS after grinding ($CDCl_3$, 500 MHz, Entry 11).

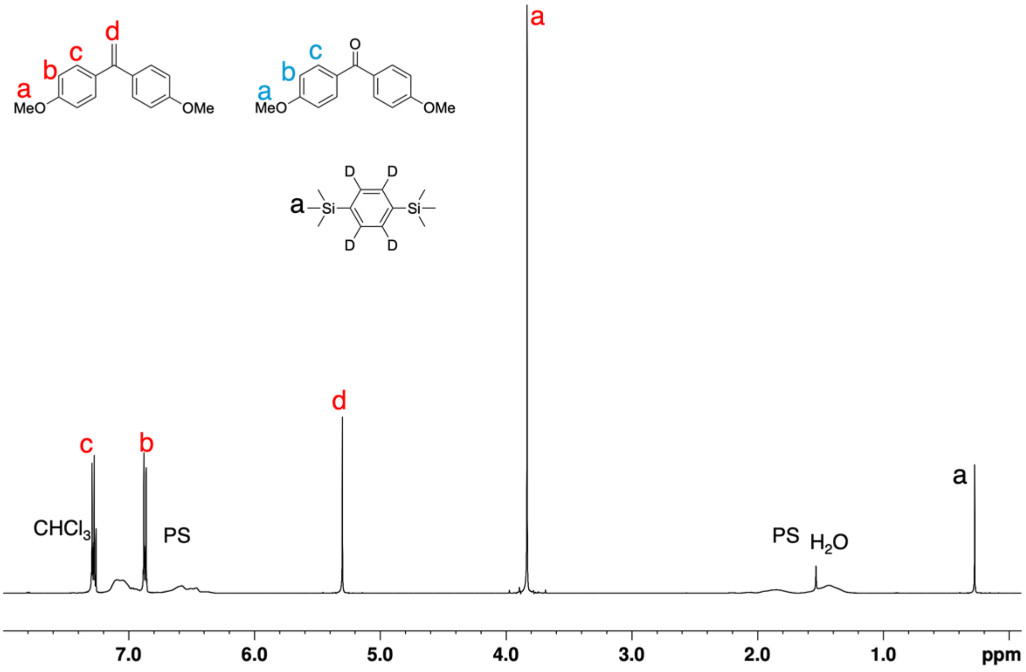

Figure S48. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** (500 µmol) and PS after grinding ($CDCl_3$, 500 MHz, Entry 12).

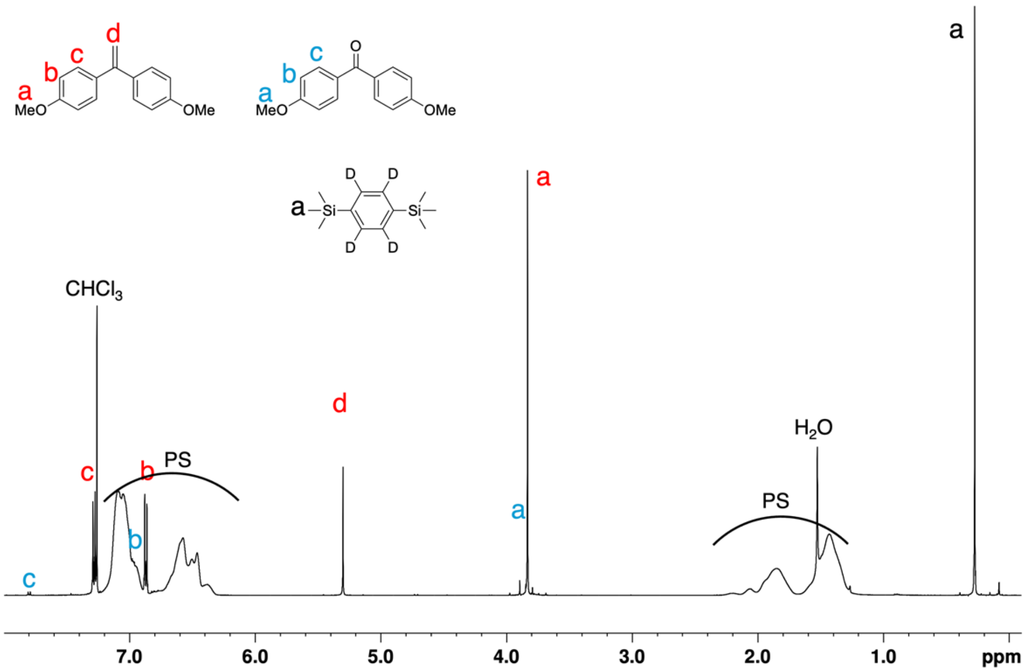

Figure S49. ^{1}H NMR spectrum of a mixture of **DAE-OMe/OMe** and PS after grinding under N_2-like conditions ($CDCl_3$, 500 MHz, Entry 1).

DAE-SMe/OMe

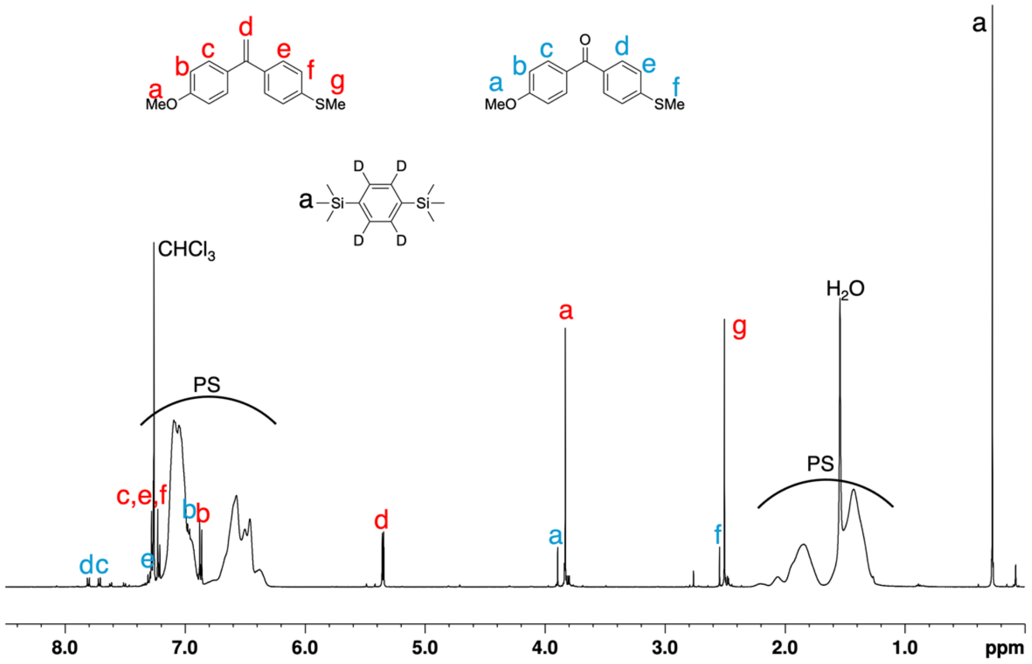

Figure S50. ^{1}H NMR spectrum of a mixture of **DAE-SMe/OMe** and PS after grinding ($CDCl_3$, 500 MHz).

DAE-H/OMe

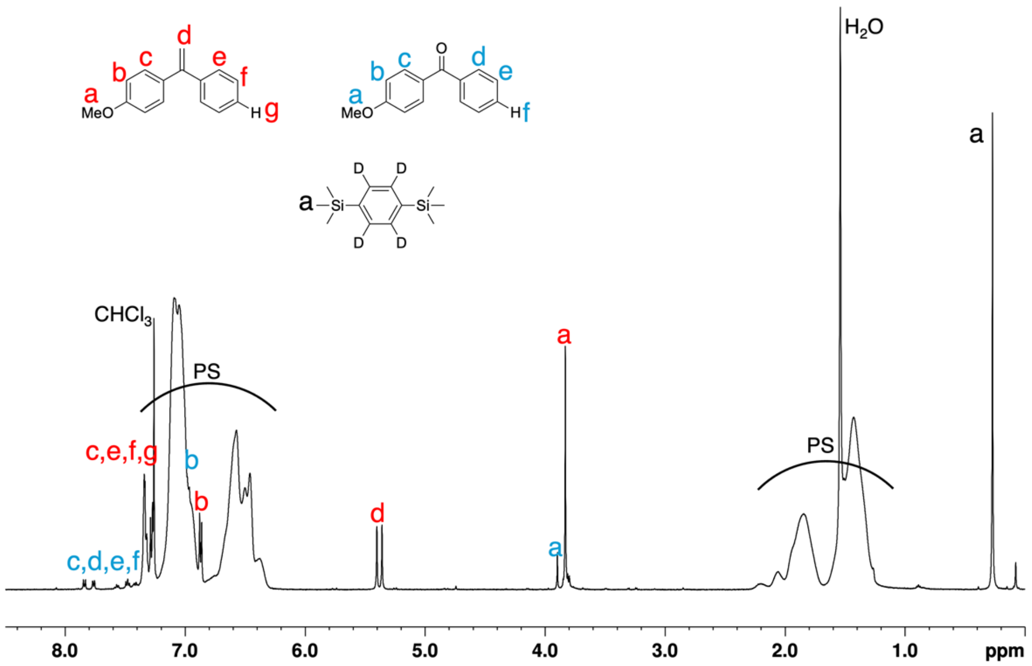

Figure S51. ^{1}H NMR spectrum of a mixture of **DAE-H/OMe** and PS after grinding ($CDCl_3$, 500 MHz).

DAE-^{t}Bu/^{t}Bu

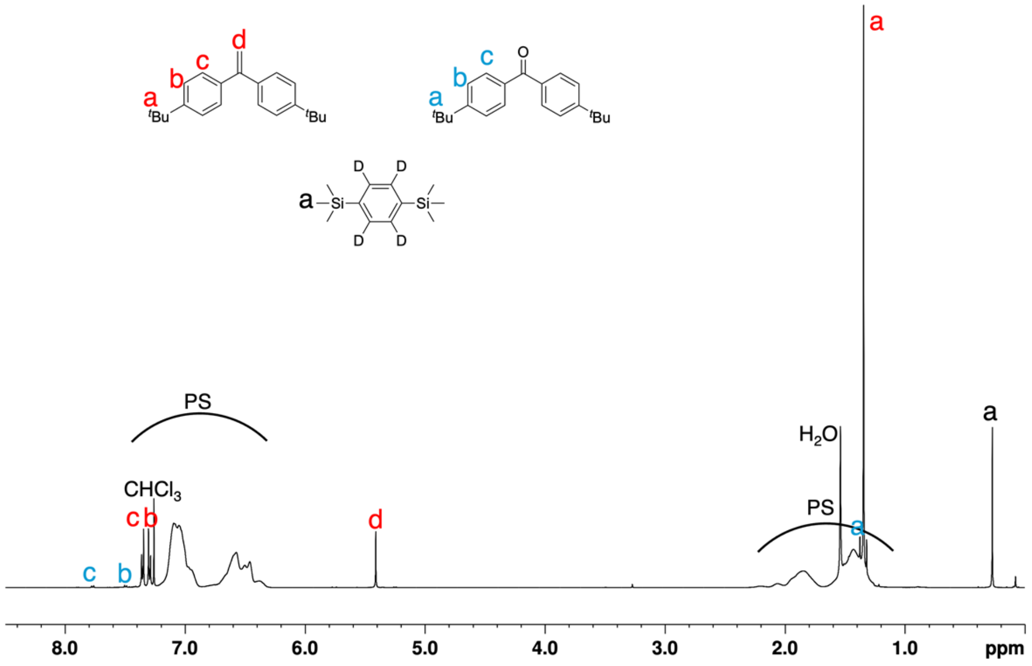

Figure S52. ^{1}H NMR spectrum of a mixture of **DAE-^{t}Bu/^{t}Bu** and PS after grinding ($CDCl_3$, 500 MHz).

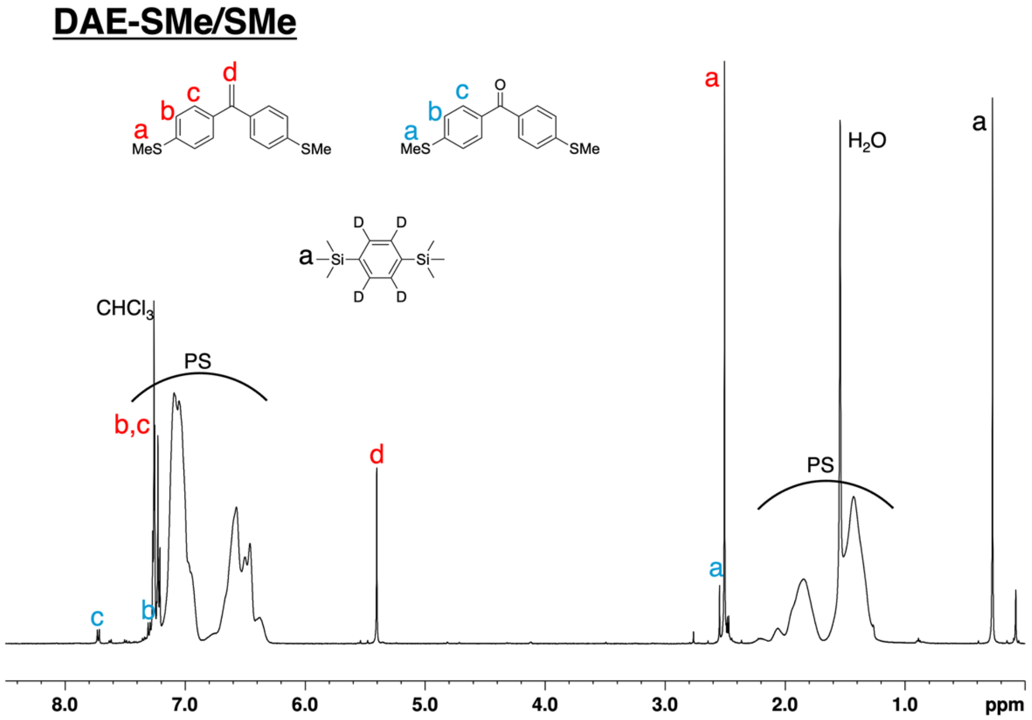

Figure S53. ^{1}H NMR spectrum of a mixture of **DAE-SMe/OMe** and PS after grinding ($CDCl_3$, 500 MHz).

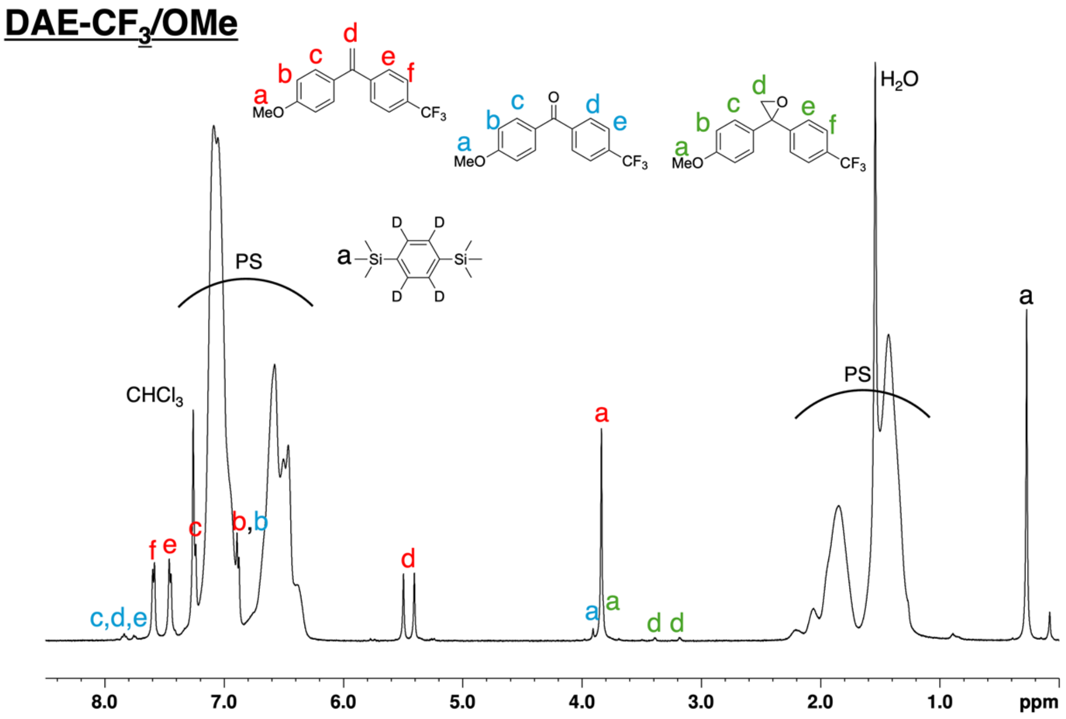

Figure S54. ^{1}H NMR spectrum of a mixture of **DAE-CF$_3$/OMe** and PS after grinding ($CDCl_3$, 500 MHz).

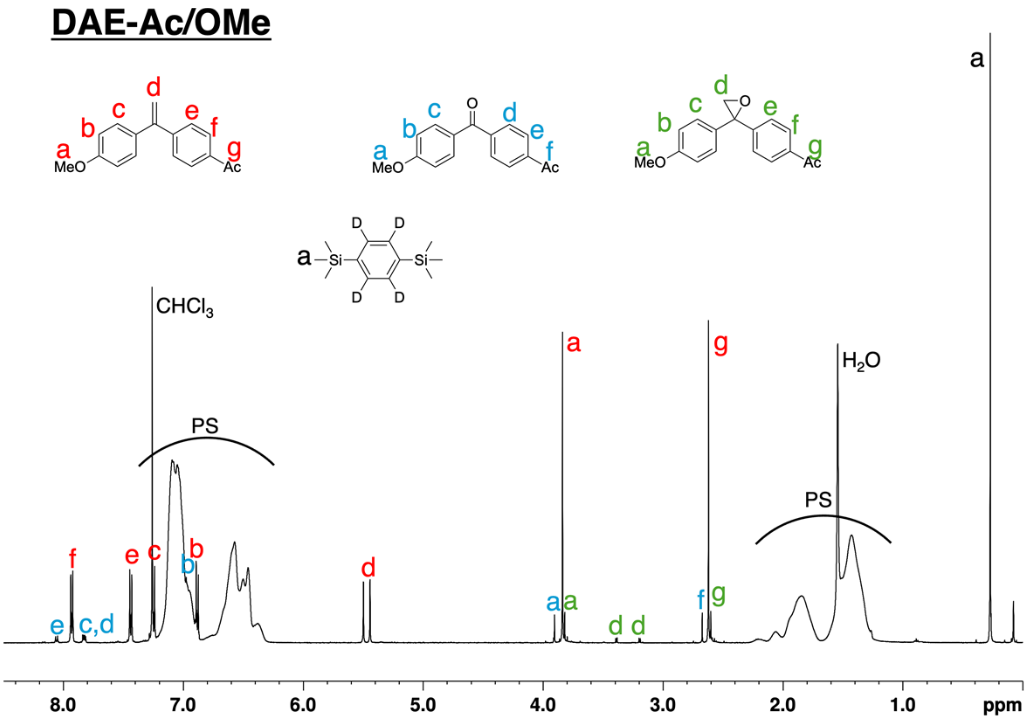

Figure S55. ^{1}H NMR spectrum of a mixture of **DAE-Ac/OMe** and PS after grinding ($CDCl_3$, 500 MHz).

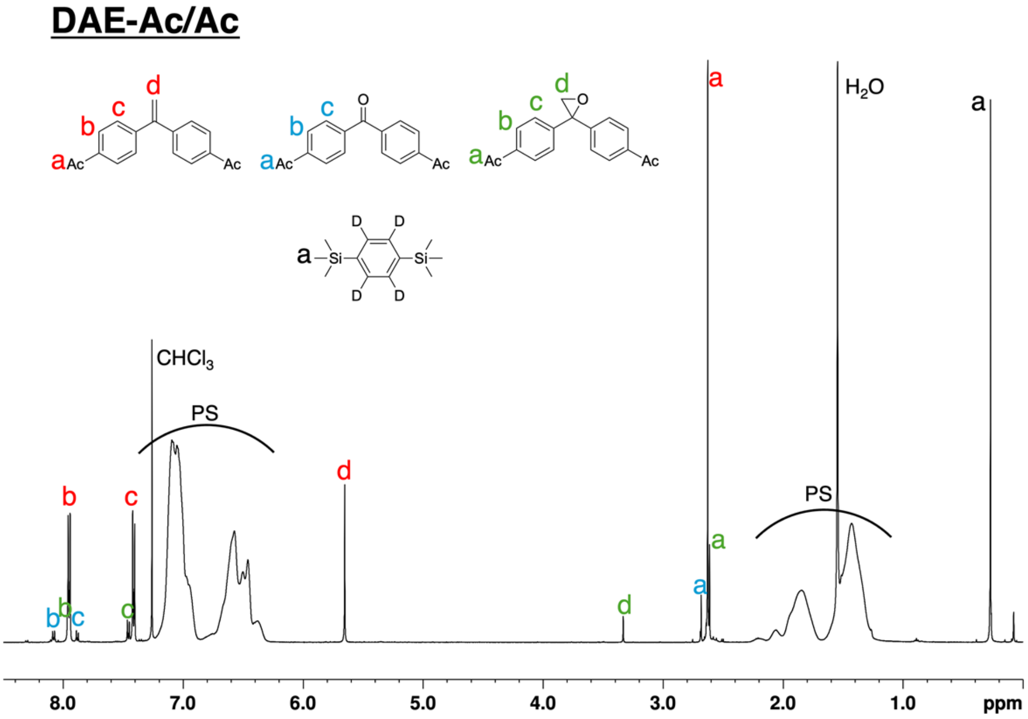

Figure S56. ^{1}H NMR spectrum of a mixture of **DAE-Ac/Ac** and PS after grinding ($CDCl_3$, 500 MHz).

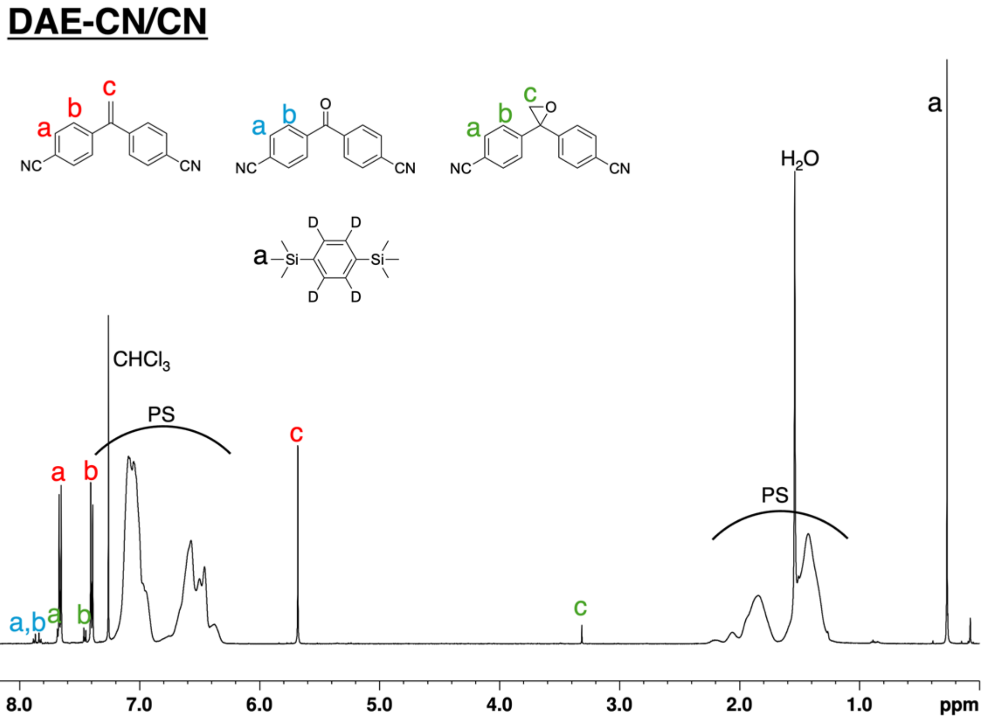

Figure S57. ^{1}H NMR spectrum of a mixture of **DAE-CN/CN** and PS after grinding (CDCl$_3$, 500 MHz).

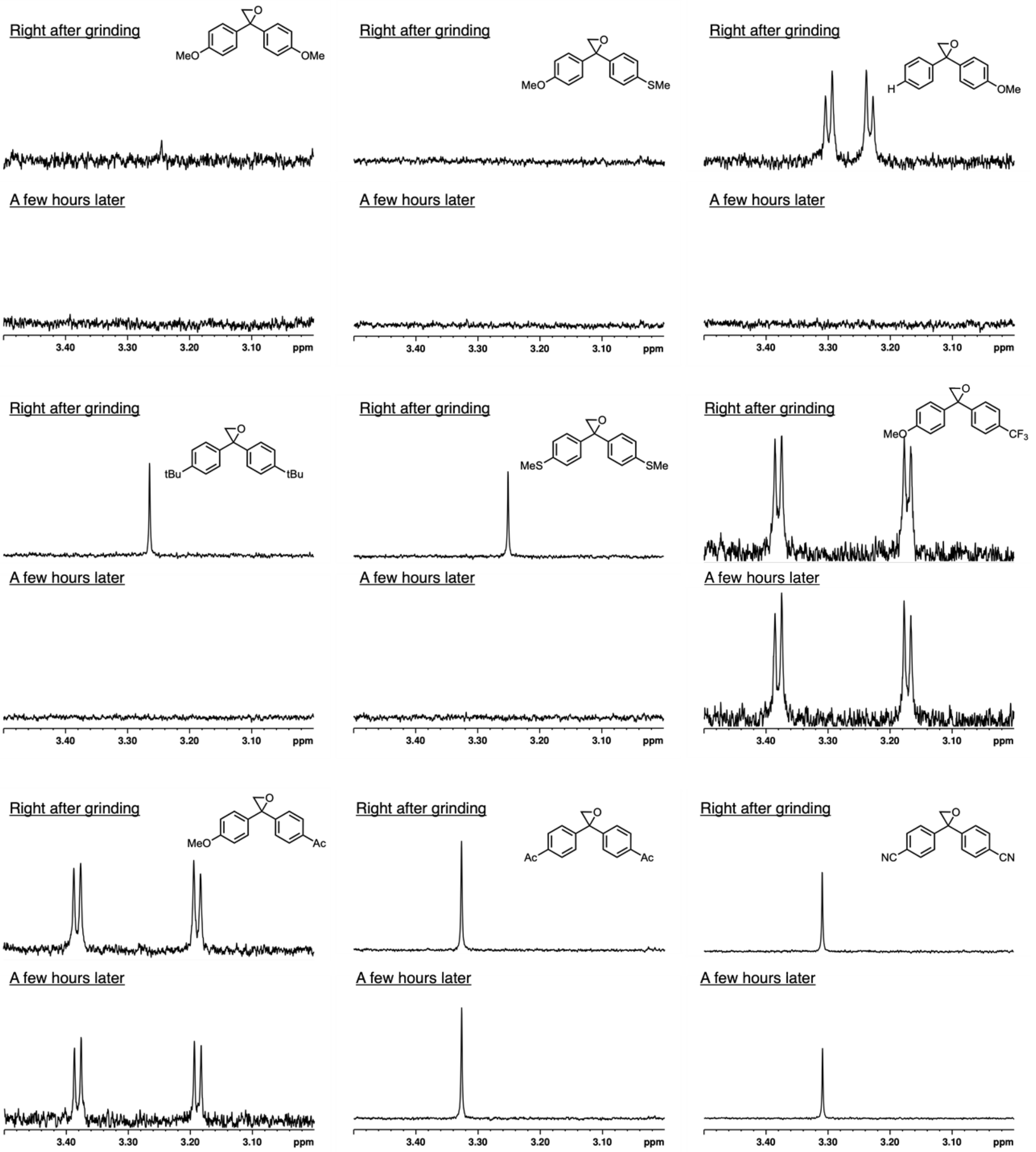

Figure S58. ^{1}H NMR spectra (3.00–3.50 ppm) of each DAE derivative mixed with PS recorded immediately after grinding and approximately 3 hours after grinding ($CDCl_3$, 500 MHz).

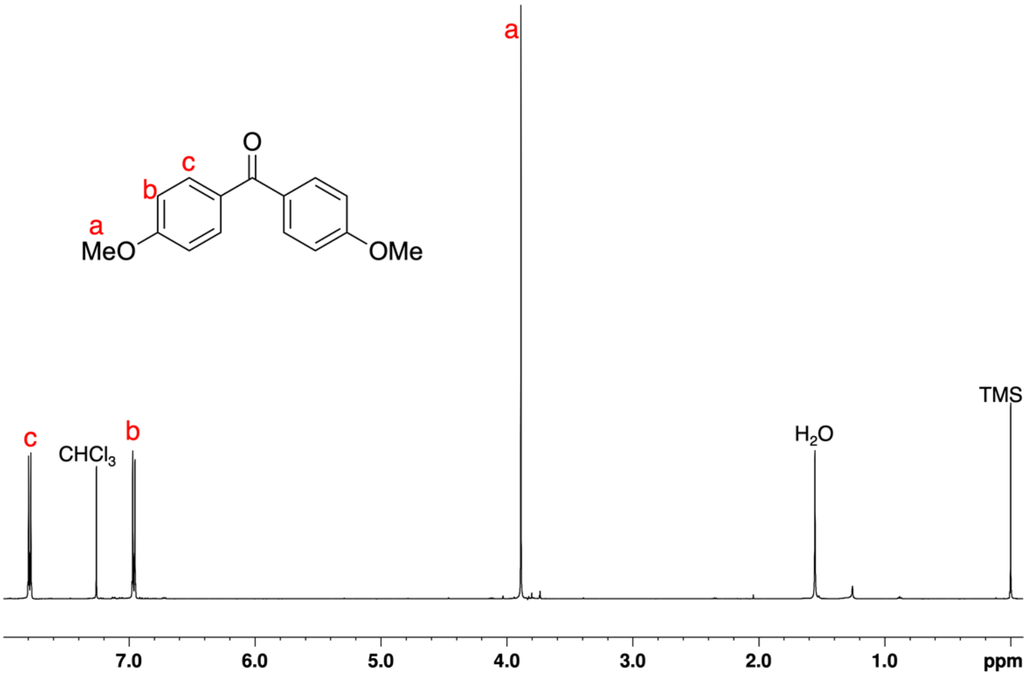

Figure S59. ^{1}H NMR spectrum of **DAK-OMe/OMe** obtained after grinding and subsequent purification.

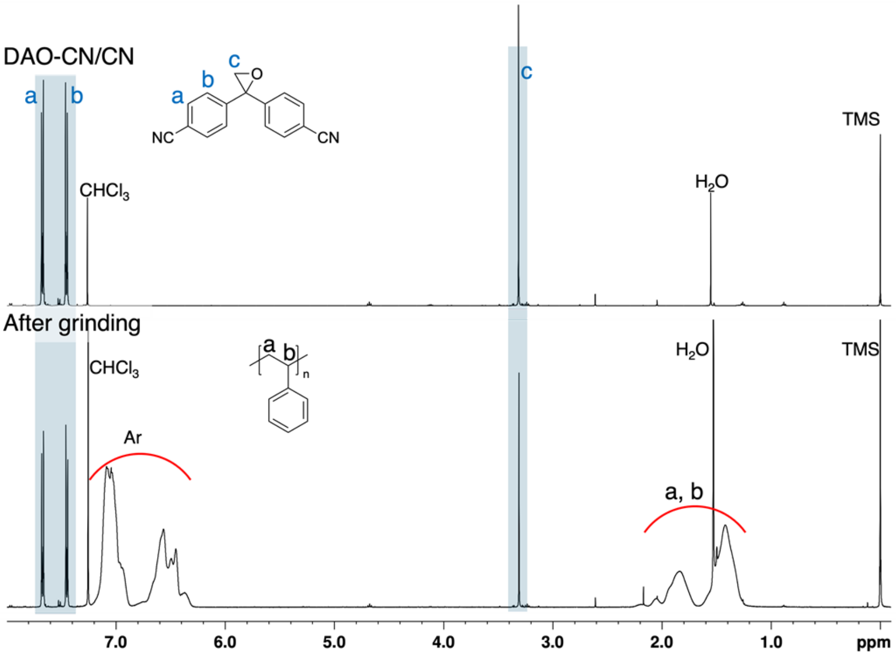

Figure S60. ^{1}H NMR spectra of (a) **DAO-CN/CN** before grinding and (b) a mixture of PS and **DAO-CN/CN** after grinding.

Ball milling of small molecules

A small molecule (ca. 100 mg) was placed in a ball-mill jar and ground under the conditions described above. The ground sample was subjected to ^1H NMR spectroscopy.

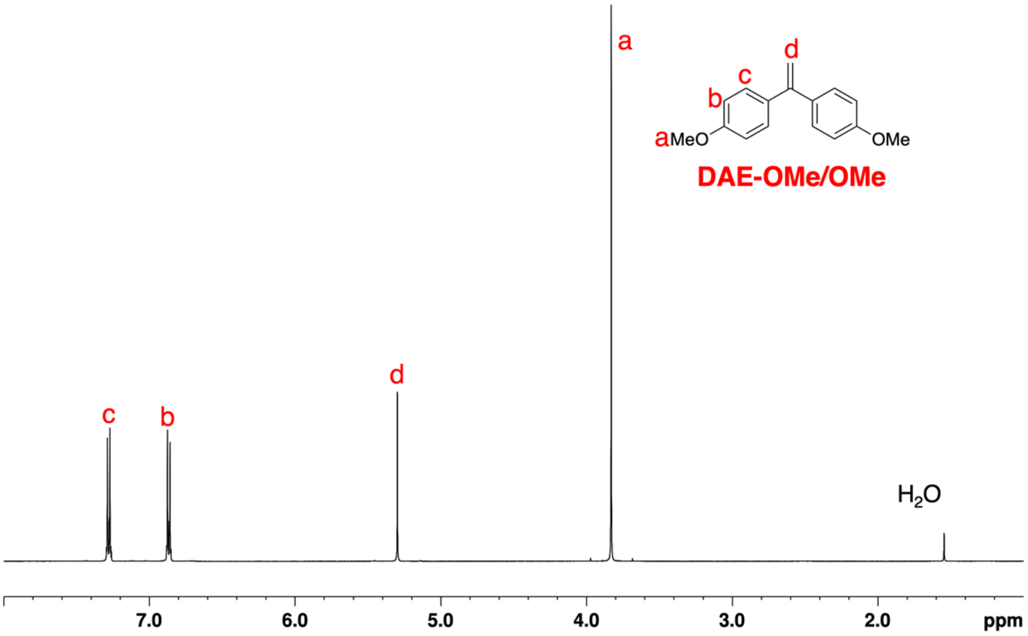

Figure S61. ^1H NMR spectrum of **DAE-OMe/OMe** after grinding ($CDCl_3$, 500 MHz).

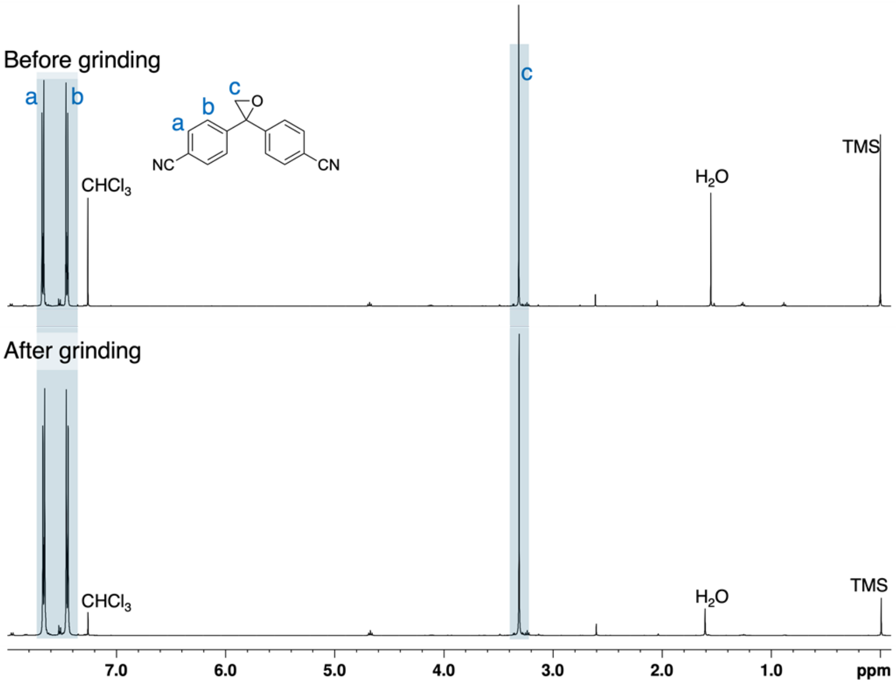

Figure S62. ^1H NMR spectra of **DAO-CN/CN** before and after grinding ($CDCl_3$, 500 MHz).

4.2 EPR Spectroscopy

Ground samples were transferred into an EPR glass capillary and weighed, and the capillary was sealed after being degassed. EPR measurements were carried out on a JEOL JES-X320 X-band EPR spectrometer. The spectra of the ground samples were recorded using a microwave power of 0.1 mW and a field modulation of 0.1 mT with a time constant of 0.03 s and a sweep rate of 0.50 $\mathrm{mTs^{-1}}$ at room temperature. The amount of radical species was determined by comparing the area of the observed integral spectrum with that of a 0.05 mM solution of 4-hydroxy-2,2,6,6-tetramethylpiperidin-1-oxyl (TEMPOL) in benzene under the same experimental conditions. The $\mathrm{Mn^{2+}}$ signal was used as an auxiliary standard. The g value was calculated according to the following equation:

$$g = h\nu/\beta H$$

where h is the Planck constant, ν is the microwave frequency, β is the Bohr magneton, and H is the magnetic field.

4.3 GPC profiles

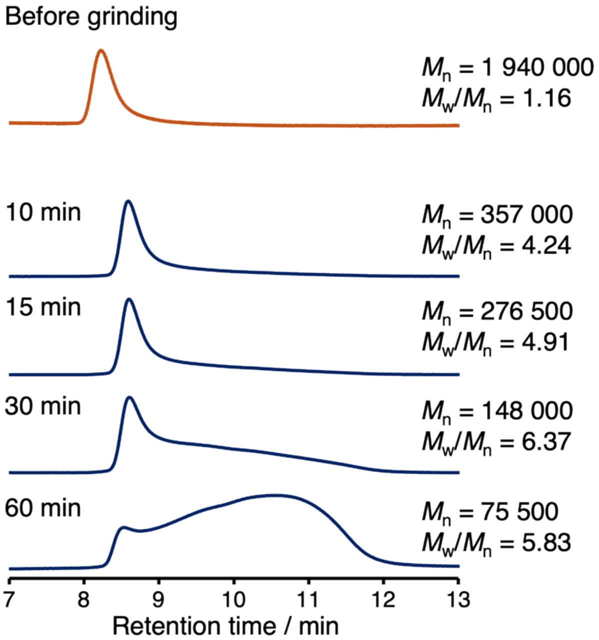

Figure S63. GPC profiles of a mixture of PS and **DAE-OMe/OMe** before and after grinding for 10, 15, 30 and 60 min (THF, RI).

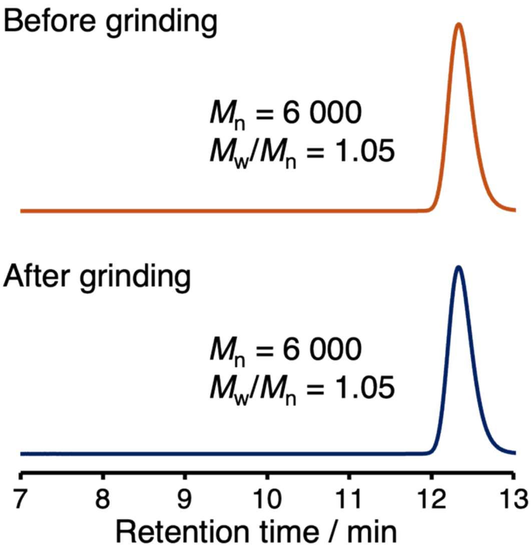

Figure S64. GPC profiles of a mixture of PS (M_n = 6,000) and **DAE-OMe/OMe** before and after grinding (THF, RI).

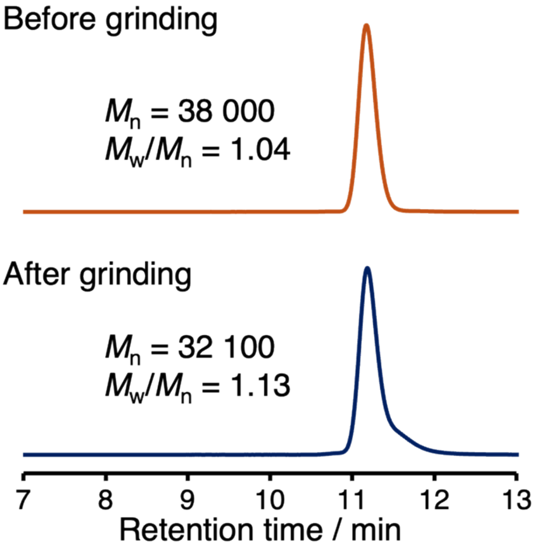

Figure S65. GPC profiles of a mixture of PS (M_n = 38,000) and **DAE-OMe/OMe** before and after grinding (THF, RI).

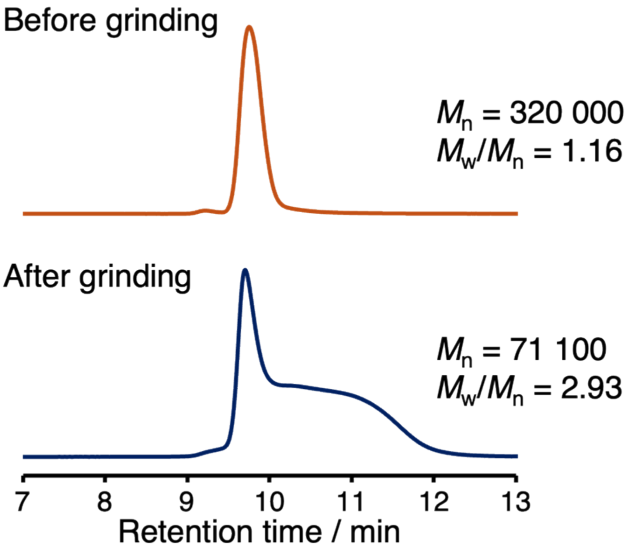

Figure S66. GPC profiles of a mixture of PS (M_n = 320,000) and **DAE-OMe/OMe** before and after grinding (THF, RI).

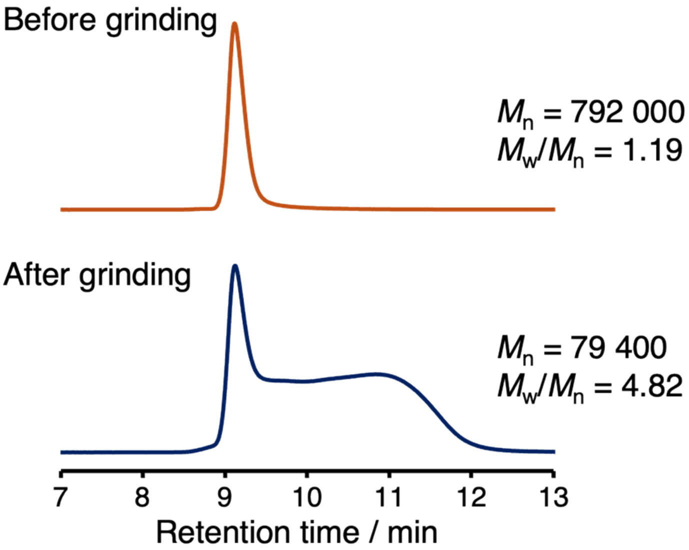

Figure S67. GPC profiles of a mixture of PS (M_n = 792,000) and **DAE-OMe/OMe** before and after grinding (THF, RI).

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