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A study of mono-, di- and tri-tosylated amines: An unexpected sulfonamide

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Abstract

2-Aminobenzylaniline was ditosylated and gave an unexpected product N,N-ditosylamino-2-benzylaminobenzene in which the primary amine had ditosylated, and the benzylamine was unreacted. The benzylamine, although more electron rich, is sterically crowded and less nucleophilic than the primary amine in this ditosylated system. Sterically crowded tosylamides were prepared by reacting *o*-phenylenediamine, *p*-phenylenediamine and 1,8-diaminonaphthalene with tosyl chloride.

Keywords

crystal structure, *o*-phenylenediamine, sulfonamide, tosylamide, tosylchloride

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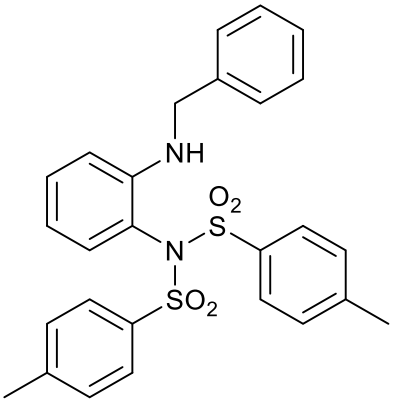

Introduction

o-Phenylenediamine **1** is readily monotosylated[1–3] with 1 equiv. of tosyl chloride **2**, to give compound **3**, or ditosylated[4,5] with 2 equiv. of tosyl chloride **2** in hot pyridine at 120 °C to give compound **4** (Scheme 1). A number of their uses are discussed in the following sections.

Condensation with ethylglyoxalate in toluene gave compound **5**, which was oxidatively cylised into the benzimidazole derivative **6** (Scheme 2).[1]

Ditosylate **4** condenses with α,α′-dibromo-*o*-xylene **7** and K_2CO_3 to give an unusual eight-membered ring heterocycle **8** and various derivatives, which were investigated for their biological properties (Scheme 3).[6]

Ditosylate **4** condenses with 1,2-dibromopropanol **9** with sodium/EtOH to form the six-membered heterocycle **10** and various derivatives (Scheme 4).[7]

Ditosylate **4** condenses with $SiCl_4$ to form a bis-spirocyclic heterocycle **11**, which is bonded around the central silicon atom (Scheme 5).[8] This utilises the subtending bite

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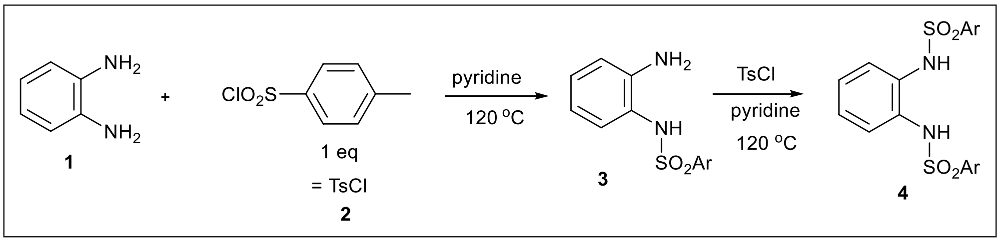
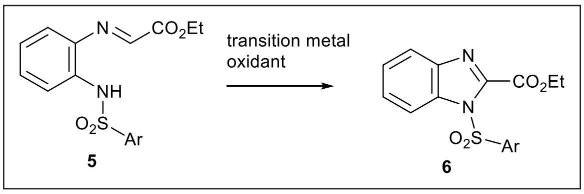
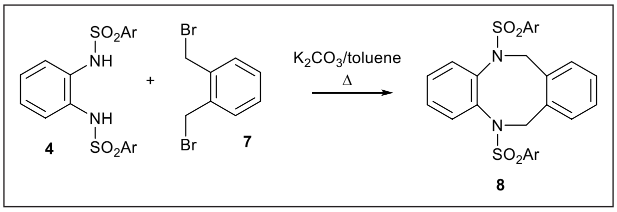


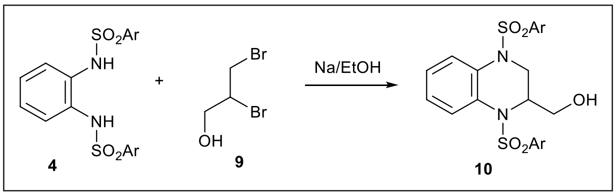
Scheme 1. The tosylation of *o*-phenylenediamine **1** in hot pyridine at 120 °C/microwave 4 min.



Scheme 2. An oxidative cyclisation forming benzimidazole derivative **6**.[1]



Scheme 3. Formation of an eight-membered ring heterocycle from ditosylate **4** and α,α′-dibromo-*o*-xylene **7**.[6]



Scheme 4. Formation of heterocycle **10**.[7]

angle of the two N atoms and the large silicon size, and orthogonal bonding prevents steric crowding. Metal complex **12** is a typical and obvious application treating ditosylate **4** as a bidentate ligand.[4]

Discussion

Compound **4** was of interest for a new method of phenazine synthesis, and its preparation led to this programme of research.[9,10] Initial studies focussed on repeating the syntheses of monotosylate **3** and ditosylate **4** by treating *o*-phenylenediamine **1** with either 1 or 2 equiv. of tosyl chloride **2** in hot pyridine at 100 °C, respectively. This works well, and only the ditosylate **4** forms using 3 equiv. of tosyl chloride **2** in pyridine. The R_f values of compounds **3** and **4** are identical with DCM as the eluent. The new compound *o*-phenylenediamine tritosylate **13** was formed in DCM with Et_3N as the base. An X-ray single-crystal structure was obtained for compounds **3**,[1–3] **4**[4–5] and **13**. The crystal structures of compounds **3** and **4** are in good agreement with previously published results[11,12] (Cambridge Structural Database[13] ref. codes UCUFOO and LAQDAJ, respectively).

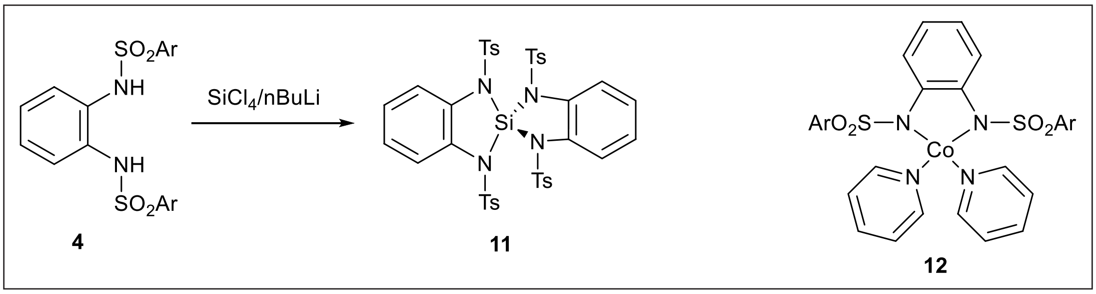
There are two molecules in the asymmetric unit of compound **13**, which crystallises in the triclinic space group $P\bar{1}$. In the C1 molecule (Figure 1), the dihedral angle between the central C1–C6 ring and the pendant C7–C12, C14–C19 and C21–C26 rings are 24.1° (2°), 31.9° (2°) and 70.03° (17°), respectively: The corresponding dihedral angles in the C28 molecule are 14.3° (3°), 28.9° (2°) and 84.29° (14°), respectively. The key torsion angles for the C1 molecule are C1–N1–S1–C7 [103.1° (4°)], C1–N1–S2–C14 [69.1° (4°)] and C2–N2–S3–C21 [52.7° (5°)], and the equivalent data for the C28 molecule are 123.3° (3°), 60.6° (4°) and 65.4° (4°), respectively. All this indicates that the C1 and C28 molecules have different conformations as shown in the overlay plot in Figure 2. In both molecules, the sulfonamide hydrogen atom is evidently too sterically crowded to form a hydrogen bond, and some weak intermolecular C–H···O links may help to consolidate the packing.

A more crowded tetratosyl-*o*-phenylenediamine derivative **14** did not form even when a reaction was performed with 4 equiv. of tosyl chloride **2** and *o*-phenylenediamine **1** (Scheme 6), presumably because compound **14** is too sterically crowded.

A successful synthesis of N,N-ditosylamino-2-benzylaminobenzene **16** was achieved by tosylating 2-aminobenzylaniline **15**[14] with 3 equiv. of tosylchloride (Scheme 7). This result was unexpected because the benzylamino group was expected to be more electron-rich and reactive towards tosyl chloride. The structure must be too crowded to form a tritosyl derivative. In the theoretical equilibrium shown in Scheme 8, compound **16** must be more stable than the unknown compound **17**. Steric crowding by the benzyl group effectively makes the benzylamino group less nucleophilic in this system, and the primary amine is more nucleophilic. The nuclear magnetic resonance (NMR) data, both proton and carbon, easily distinguished compound **16** from compound **17**.

The tosylation of 1,8-diaminonaphthalene **18** gave a mixture of two products, a tritosyl derivative **19** and a ditosyl derivative **20** (Scheme 9). An X-ray single-crystal structure determination was performed on compound **19**.

Compound **19** crystallises with one molecule in the asymmetric unit (Figure 3) in the orthorhombic space group *Pbca*. The dihedral angles between the C1–C10 naphthalene ring mean plane (root-mean-square deviation = 0.005



Scheme 5. Formation of herocycle **11**[8] and metal-ion complex **12**.[4]

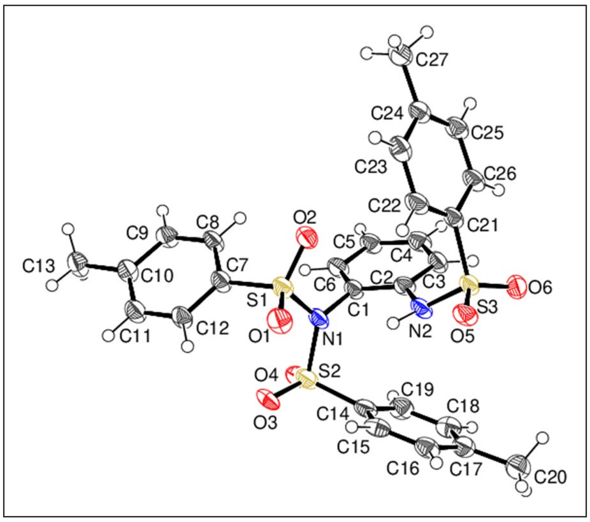


Figure 1. The C1 molecule in compound **13** (57% yield) showing 50% displacement ellipsoids.

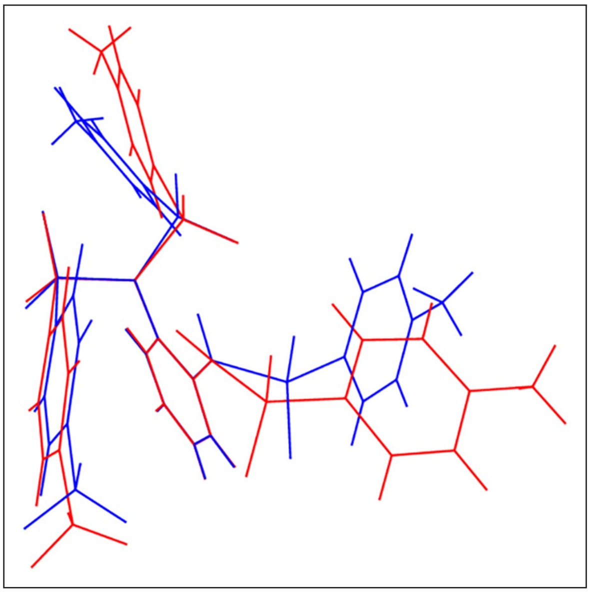
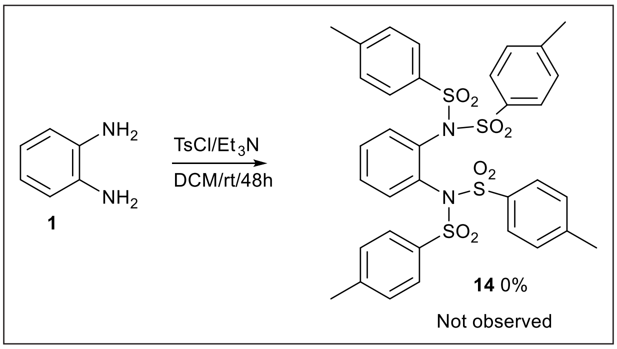
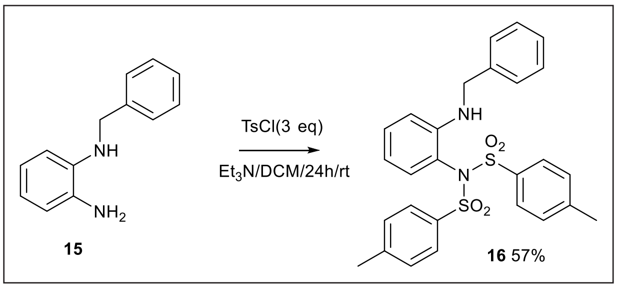


Figure 2. Overlay plot of the C1 (red) and C28 (blue) molecules in the crystal of compound **13**, with the C1–C6 and C28–C33 rings superimposed.

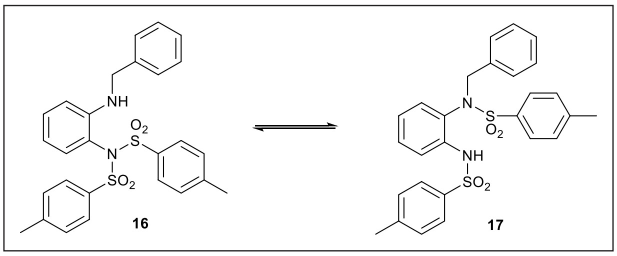
Å) and the C11–C16, C18–C23 and C25–C30 phenyl rings are 52.08° (3°), 14.40° (5°) and 84.41° (4°), respectively. The C1–N1–S1–C11 torsion angle is −56.40° (11°) with corresponding values of 94.13° (10°) for C1–N1–S2–C18 and 57.15° (13°) for C9–N2–S3–C25. An intramolecular N2–H1···N1 hydrogen bond with H···N = 2.177 (19) Å and N–H···N = 135.6° (16°) occurs [compare the C2–C1–N1–S1 and C2–C1–N1–S2 torsion angles of 78.86° (13°) and −84.24° (13°), respectively], and a weak C8–H8···O6 bond may help to establish the conformation.



Scheme 6. Tetratosyl-*o*-phenylenediamine derivative **14** which failed to form.

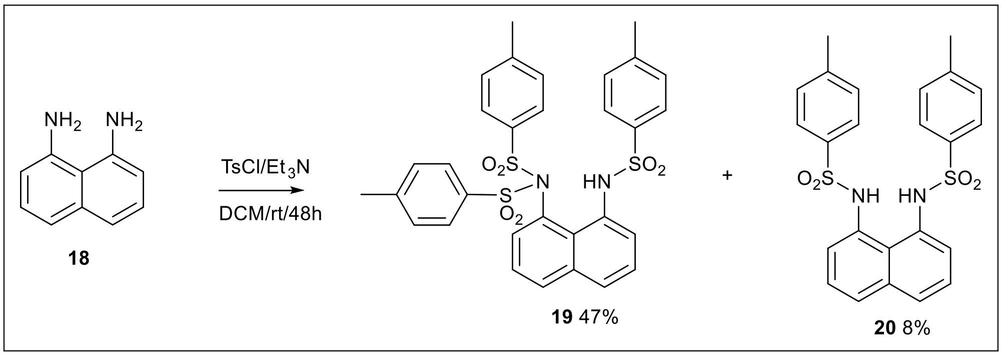


Scheme 7. The formation of N,N-ditosylamino-2-benzylaminobenzene **16.**



Scheme 8. Theoretical equilibrium between two ditosylated derivatives of 2-benzylaminoaniline **15.**

The synthesis of a tetratosylated derivative of *p*-phenylenediamine **21** is shown in Scheme 10. Less crowding occurs around each sulfonamide, so the synthesis is as expected. The compound is soluble in DCM. These



Scheme 9. The synthesis of tri- and di-tosylated-1,8-diaminonaphthalenes **19** and **20**.

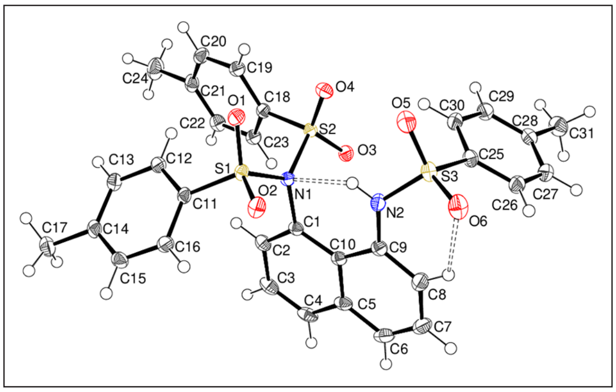


Figure 3. The molecular structure of compound **19** showing 50% displacement ellipsoids with hydrogen bonds indicated by double-dashed lines.

molecules may find applications as rotamers as they are big enough to attach to a surface non-covalently and move across it.

Treatment of *o*-phenylenediamine **1** with 3 equiv. of (1*S*)-(+)-10-camphorsulfonyl chloride **23** gave the trifunctionalised derivative **24** (Scheme 11). This compound is waxy, and no X-ray single-crystal structure was obtained for it. The aliphatic proton NMR was too complicated to be interpreted with many overlapping signals, but the aromatic region showed two doublets and two triplets as expected. The carbon-13 spectrum was well resolved. The signals appeared in groups of three, which showed that three different camphor groups were present. There were six methyl groups, six aryl carbons and three carbonyl groups (Supplemental Material). This observation suggests that compound **24** is sterically crowded with the two different camphoryl groups attached to the same N atom. Restricted rotation around the Ar–N bond might explain this if it is slow on an NMR timescale.

Conclusion

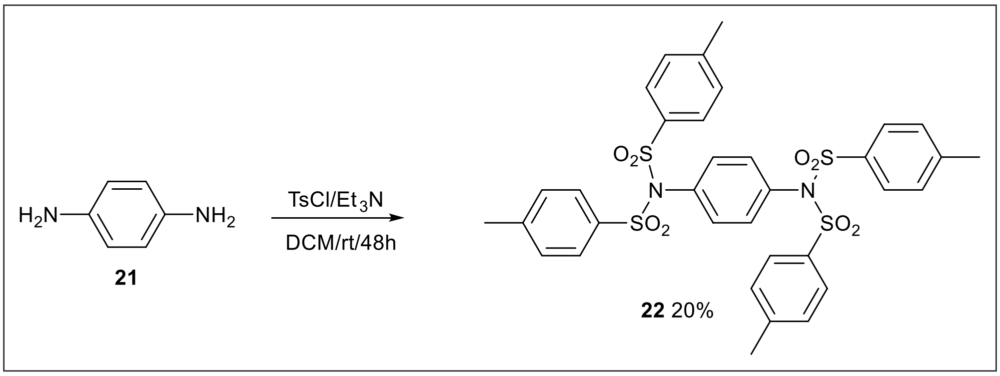
o-Phenylenediamine **1** was mono-, di- and tri-tosylated with tosyl chloride in either hot pyridine at 100 °C or DCM to give mono-, di- or tri-tosyl-*o*-phenylenediamines **3**, **4** or **13**, respectively. 1,8-Diaminonaphthalene **18** was di- and tri-tosylated to give the corresponding di- and tri-tosylated-1,8-aminonaphthalenes, respectively. 2-Aminobenzylaniline **15** was ditosylated and gave an unexpected product N,N-ditosylamino-2-benzylaminobenzene **16** in which the primary amine had ditosylated, and the benzylamine was unreacted. The benzylamine, although more electron-rich, is sterically crowded and less nucleophilic than the primary amine in this ditosylated system. The two possible ditosylated products **16** and **17** were easily distinguished by proton and ^{13}C NMR. X-ray single-crystal structure determinations were performed on compounds **3**, **4**, **13** and **19**. In no case did we observe tetratosylated derivatives from o-phenylenediamine **1** which are too sterically crowded to form. Tritosylate **19** displayed an intramolecular hydrogen bond between the two nitrogen atoms similar to that seen in the protonation of proton sponge.[15–17] Compound **24** has three different camphoryl groups in it (see Supplemental Material).

Experiment

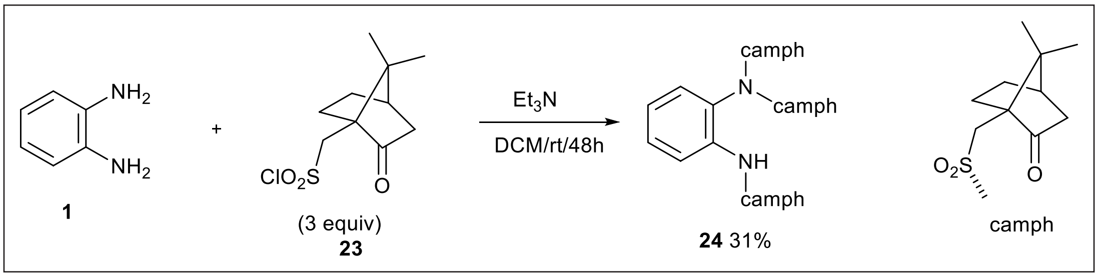
Infrared (IR) spectra were recorded on a diamond attenuated total reflection Fourier-transform IR spectrometer. Ultraviolet (UV) spectra were recorded using a PerkinElmer Lambda 25 UV-Vis spectrometer with EtOH as the solvent. The term 'sh' means shoulder. ^{1}H and ^{13}C NMR spectra were recorded at 400 and 100.5 MHz, respectively, using a Varian 400 spectrometer. Chemical shifts, δ, are given in ppm and measured by comparison with the residual solvent. Coupling constants, *J*, are given in Hz. The term 'br' stands for broad. High-resolution mass spectra were obtained at the University of Wales, Swansea, using an Atmospheric Solids Analysis Probe (ASAP) (positive mode) Instrument: Xevo G2-S ASAP. Melting points were determined on a Kofler hot-stage microscope.

N-(2-Aminophenyl)-4-methylbenzenesulfonamide 3

o-Phenylenediamine (255 mg, 2.36 mmol) and tosyl chloride (450 mg, 2.36 mmol) were mixed in CH_2Cl_2 at room temperature with Et_3N (477 mg, 4.72 mmol) for 24 h. The organic layer was extracted with water (100 ml), then dried with $MgSO_4$ and filtered. The desired product was purified by chromatography on silica gel. Elution with Et_2O/CH_2Cl_2 (20:80) then Et_2O/CH_2Cl_2 (50:50) gave the *title compound* (394 mg, 64%) as a white solid,



Scheme 10. The synthesis of N,N,N′,N′-tetratosyl-1,4-diaminobenzene **22.**



Scheme 11. The synthesis of N,N,N′-tricamphoryl-1,2-diaminobenzene tentatively assigned as structure **24**.

m.p. 140–141 °C (from dichloromethane:light petroleum ether). λ_{max} (EtOH)/nm 219 (log ε 4.3) and 291 (3.5); ν_{max} (diamond)(cm^{-1}) 3467w, 3385w, 3208w, 1622w, 1597w, 1497w, 1464w, 1316s, 1148vs, 1091s, 813w, 751s, 672vs, 532vs and 473s; δ_H (400 MHz; CDCl$_3$) 2.41 (3H, s), 6.54 (2H, d, $J=4.0$), 6.76 (1H, d, $J=8.0$), 7.03 (1H, m), 7.23 (2H, d, $J=8.0$) and 7.64 (2H, d, $J=8.0$); δ_C (100.1 MHz; CDCl$_3$) 21.7, 117.3, 118.9, 121.5, 127.5, 128.5, 128.8, 129.7, 136.0, 143.8 and 143.9; *m/z* (Orbitrap ASAP) 263.0843 (M + H$^+$, 100%) $C_{13}H_{14}N_2O_2S + H^+$ requires 263.0849.

N,N′-1,2-Phenylenebis(4-methylbenzenesulfonamide) 4

ortho-Phenylenediamine **1** (0.5 g, 4.6 mmol) and tosyl chloride **2** (1.77 g, 9.3 mmol) were mixed in pyridine (20 ml) and heated at 100 °C for 1 h. The mixture was cooled and added to water, left standing, filtered and washed with plenty of water to give the *title compound* (1.6 g, 84%) as an off-white solid, m.p. 204–205 °C (Lit 202 °C)[1]. λ_{max} (EtOH)/nm 231 (log ε 4.1); ν_{max} (diamond) (cm^{-1}) 3220w, 1596w, 1498w, 1324s, 1146vs, 1087s, 936w, 836w, 810s, 762s, 662 and 542vs; δ_H (400 MHz; CDCl$_3$) 2.41 (6H, s), 6.90–6.96 (2H, s, br), 6.97 (1H, d, $J=4.0$), 6.99 (1H, t, $J=4.0$ and 4.0), 7.04 (1H, t, $J=4.0$ and 4.0), 7.06 (1H, d, $J=4.0$), 7.24 (4H, d, $J=8.0$) and 7.60 (4H, d, $J=8.0$); δ_C (100.1 MHz; CDCl$_3$) 21.6, 126.1, 127.4, 127.5, 129.6, 130.8, 135.4 and 144.2; *m/z* (Orbitrap ASAP) 417.0940 (M + H$^+$, 100%) $C_{20}H_{21}N_2O_4S_2$ requires 417.0943.

N-(2-{bis[(4-Methylphenyl) sulfonyl]amino}phenyl)-4-methylbenzenesulfonamide 13

o-Phenylenediamine **1** (0.5 g, 4.6 mmol) and tosyl chloride **2** (2.65 g, 13.9 mmol) were mixed in CH$_2$Cl$_2$ (50 ml) at room temperature with Et$_3$N (1.4 g, 13.9 mmol) for 24 h.[18–20] The organic layer was extracted with water (100 ml) then dried with MgSO$_4$ and filtered. The desired product was purified by chromatography on silica gel. Elution with Et$_2$O/CH$_2$Cl$_2$ (20:80) then Et$_2$O/CH$_2$Cl$_2$ (50:50) gave the *title compound* (1.5 g, 57%) as a white solid, m.p. 158–159 °C (from dichloromethane:light petroleum ether). λ_{max} (EtOH)/nm 240 (log ε 3.8); ν_{max} (diamond)(cm^{-1}) 3375w, 1596w, 1492w, 1376s, 1158s, 1084w, 902s, 855w, 810w, 666vs, 546vs, 499w and 487w; δ_H (400 MHz; CDCl$_3$) 2.41 (3H, s), 2.50 (6H, s), 6.65 (1H, dd, $J=8.0$ and 4.0), 6.88 (1H, td, $J=8.0$ and 4.0), 7.26-7.32 (3H, m), 7.38 (4H, d, $J=8.0$), 7.44 (1H, dd, $J=8.0$ and 4.0), 7.83 (4H, d, $J=8.0$) and 7.85 (2H, d, $J=8.0$); δ_C (100.1 MHz; CDCl$_3$) 21.9, 117.8, 122.6, 123.0, 127.6, 129.0, 129.7, 129.9, 131.5, 132.7, 135.3, 136.5, 137.5, 144.1 and 146.0; *m/z* (Orbitrap ASAP) 588.1302 (M + NH$_4^+$, 100%) $C_{27}H_{26}N_2O_6S_3 + NH_4^+$ requires 588.1297.

N,N-Ditosyl-1-amino-2-benzylaminobenzene 16

N-Benzyl-*o*-phenylenediamine **15** was prepared by a literature method.[9] N-Benzyl-*o*-phenylenediamine **15** (200 mg, 1.0 mmol) in DCM (50 ml) was mixed with tosyl chloride

(578 mg, 3.0 mmol) and Et_3N (306 mg, 3.0 mmol) for 24 h. The organic layer was extracted with water (100 ml), then dried with $MgSO_4$ and filtered. The desired product was purified by chromatography on silica gel. Elution with Et_2O/CH_2Cl_2 (20:80) and then Et_2O/CH_2Cl_2 (50:50) gave the *title compound* (290 mg, 57%) as an off-white solid, m.p. 151–152 °C (from dichloromethane:light petroleum ether). The product is an oil, which slowly crystallises over a few days with scratching. λ_{max} (EtOH)/nm 316 (log ε 2.9) and 231sh (3.7); ν_{max} (diamond)(cm^{-1}) 1595w, 1507w, 1453w, 1350s, 1366s, 1161s, 1120s, 1161s, 1120w, 1080w, 890s, 839w, 817w, 725w, 694w, 662w, 564s and 536s; δ_H (400 MHz; $CDCl_3$) 2.46 (6H, s), 4.27 (2H, d, *J*=4.0), 4.64–4.69 (1H, br, NH), 6.63 (1H, t, *J*=8.0 and 8.0), 6.72 (2H, m), 7.29 (5H, d, *J*=8.0), 7.35–7.42 (5H, m) and 7.94 (4H, d, *J*=8.0); δ_C (100.1 MHz; $CDCl_3$) 21.8, 47.6, 112.5, 116.6, 119.5, 127.2, 127.3, 128.7, 128.9, 129.7, 131.8, 132.7, 136.4, 138.6, 145.4 and 147.6; *m/z* (Orbitrap ASAP) 507.1410 ($M+H^+$, 100%) $C_{27}H_{27}N_2O_4S_2$ requires 507.1412 ($M+H^+$)

N-(8-{bis[(4-Methylphenyl)sulfonyl]amino}-1-naphthyl)-4-methylbenzenesulfonamide 19 and N,N′-naphthalene-1,8-diylbis(4-methylbenzenesulfonamide) 20

1,8-Diaminonaphthalene **18** (500 mg, 3.2 mmol) in DCM (50 ml) was mixed with tosyl chloride (2.42 g, 12.8 mmol) and Et_3N (1.28 g, 12.8 mmol) for 48 h.[21–23] The organic layer was extracted with dilute aqueous 2 M HCl (100 ml), then dried with $MgSO_4$ and filtered. The desired product was purified by chromatography on silica gel. Elution with Et_2O/CH_2Cl_2 (20:80) and then with Et_2O/CH_2Cl_2 (50:50) gave the first *title compound* (931 mg, 47%) as an off-white solid, m.p. 210–211 °C (from dichloromethane:light petroleum ether). λ_{max} (EtOH)/nm 320 (log ε 3.0) and 235 (3.8); λ_{max} (diamond)(cm^{-1}) 1595w, 1371s, 1349s, 1294s, 1187s, 1159s, 1084s, 1018s, 934s, 809s, 752w, 659s and 539s; δ_H (400 MHz; $CDCl_3$) 2.21 (3H, s), 2.40 (6H, s), 6.75 (1H, d, *J*=8.0), 7.09 (2H, d, *J*=8.0), 7.14 (1H, t, *J*=8.0 and 8.0), 7.21 (1H, t, *J*=8.0 and 8.0), 7.30 (4H, d, *J*=8.0), 7.39 (1H, d, *J*=8.0), 7.47 (1H, d, *J*=8.0), 7.76 (1H, d, *J*=8.0), 7.80 (4H, d, *J*=8.0), 7.81 (2H, d, *J*=8.0) and 8.79 (1H, s); δ_C (100.1 MHz; $CDCl_3$) 21.5, 22.0, 114.1, 122.1, 123.9, 124.5, 126.3, 128.2, 128.5, 129.4, 129.7, 130.3, 132.7, 132.8, 133.1, 133.9, 136.0, 136.5, 143.7 and 146.4; *m/z* (Orbitrap ASAP) 621.1187 ($M+H^+$, 100%) $C_{31}H_{28}N_2O_6S_3H$ requires 621.1188 ($M+H^+$), followed by the second *title compound* (122 mg, 8 %) as an off-white solid, m.p. 211–212 °C (from dichloromethane:light petroleum ether). λ_{max} (EtOH)/nm 320 (log ε 3.5) and 225 (4.3); ν_{max} (diamond)(cm^{-1}) 3214s, 1597w, 1560w, 1454w, 1414w, 1341w, 1297s, 1150s, 1121w, 1092s, 1042s, 905w, 814s, 708s, 656s, 559s, 543 and 487s; δ_H (400 MHz; $CDCl_3$) 2.38 (6H, s), 7.06 (2H, d, *J*=8.0), 7.23 (4H, d, *J*=8.0), 7.28 (2H, d, *J*=8.0), 7.65 (2H, d, *J*=8.0), 7.72 (4H, d, *J*=8.0), 8.60 (2H, s); δ_C (100.1 MHz; $CDCl_3$) 21.6, 123.4, 123.8, 125.6, 127.7, 128.2, 129.6, 131.3, 135.2, 136.2 and 144.3; *m/z* (Orbitrap ASAP) 467.1100 ($M+H^+$, 100%) $C_{24}H_{22}N_2O_4S_2H$ requires 467.1099 ($M+H^+$).

N,N,N′,N′-Tetratosyl-1,4-diaminobenzene 22

p-Phenylenediamine **21** (500 mg, 4.6 mmol) in DCM (50 ml) was mixed with tosyl chloride (3.53 g, 18.5 mmol) and Et_3N (1.87 g, 18.5 mmol) for 48 h. The organic layer was extracted with dilute aqueous 2 M HCl (100 ml), then dried with $MgSO_4$ and filtered. The desired product was purified by chromatography on silica gel. Elution with CH_2Cl_2/light petroleum ether (50:50) then CH_2Cl_2 gave the *title compound* (650 mg, 20%) as a white solid, m.p. 252–253 °C (from dichloromethane:light petroleum ether). λ_{max} (EtOH)/nm 233 (log ε 3.4); ν_{max} (diamond)(cm^{-1}) 1596w, 1493w, 1377s, 1360s, 1158s, 1084s, 1017w, 928s, 811s, 702w, 677w, 657s, 606s and 546s; δ_H (400 MHz; $CDCl_3$) 2.48 (12H, s), 7.03 (4H, s), 7.36 (8H, d, *J*=8.0) and 7.82 (8H, d, *J*=8.0); δ_C (100.1 MHz; $CDCl_3$) 21.7, 128.6, 129.7, 132.3, 135.9, 136.2 and 145.2; *m/z* (Orbitrap ASAP) 725.1116 ($M+H^+$, 100%) $C_{34}H_{32}N_2O_8S_4$ requires 725.1120 ($M+H^+$).

N,N,N′-Tricamphoryl-1,2-diaminobenzene 24

o-Phenylenediamine **1** (500 mg, 4.6 mmol) in DCM (50 ml) was mixed with (1*S*)-(+)-10-camphorsulfonyl chloride **23** (3.5 g, 14.0 mmol) and Et_3N (1.4 g, 14.0 mmol) for 48 h. The organic layer was extracted with dilute aqueous 2 M HCl (100 ml) then dried with $MgSO_4$ and filtered. The desired product was purified by chromatography on silica gel. Elution with Et_2O/light petroleum ether (50:50) and then with Et_2O gave the *title compound* (1.09 g, 31%) which solidified to a white, amorphous solid with scratching over 3 days. λ_{max} (EtOH)/nm 222 (log ε 4.0) and 280 (3.3); ν_{max} (diamond)(cm^{-1}) 2958m, 1739s, 1494w, 1773s, 1351m, 1150s, 1051m, 886w, 850w, 756w, 720w, 599m, 564s, 525s and 498s; δ_H (400 MHz; $CDCl_3$) (aromatic region) 7.19 (1H, t, *J*=8.0), 7.43 (1H, d, *J*=8.0), 7.46 (1H, t, *J*=8.0), 7.83 (1H, d, *J*=8.0) and 8.02 (1H, s, br, NH); δ_C (100.1 MHz; $CDCl_3$) 19.6, 19.7, 19.71, 19.8, 19.9, 19.95 (6 methyl groups), 25.4, 26.1, 26.8, 26.9, 42.5, 42.7, 42.71, 42.8, 42.81, 42.9, 48.1, 48.2, 48.5, 51.8, 52.4, 53.7, 59.0, 59.1, 59.3, 122.4, 124.5, 124.8, 131.7, 132.0, 137.4 (6 aromatic carbons) 213.6, 214.3 and 215.6 (3 carbonyl groups) (two resonances are overlapping); *m/z* (Orbitrap ASAP) 751.2769 ($M+H^+$, 5.0%) $C_{36}H_{50}N_2O_9S_3H$ requires 751.2757 ($M+H^+$).

Crystal structures

The crystal structures of **3** (colourless needle, 0.61 × 0.03 × 0.03 mm, recrystallised dichloromethane:light petroleum ether), **4** (colourless needle 0.29 × 0.04 × 0.03 mm, recrystallised from dichloromethane:light petroleum ether), **13** (colourless lath, 0.30 × 0.04 × 0.01 mm, recrystallised from dichloromethane:light petroleum ether) and **19** (colourless prism, 0.22 × 0.20 × 0.06 mm, recrystallised from dichloromethane:light petroleum ether) were established using intensity data collected at 100 K on a Rigaku CCD diffractometer using Cu Kα radiation ($\lambda = 1.54178$ Å). The structures were routinely solved by dual-space methods using SHELXT,[18] and the structural models were completed and optimised by refinement against $|F|^2$ with SHELXL-2019.[19] The N-bound hydrogen atoms were located in difference maps: For compound **3**, they were refined as riding atoms in their as-found relative positions, and for compounds **4** and **13**, their positions were freely refined. The carbon-bound hydrogen atoms were placed in idealised locations (C–H = 0.95–0.98 Å) and refined as riding atoms. The constraint $U_{iso}(H) = 1.2U_{eq}$ (carrier) or $1.5U_{eq}$ (methyl carrier) was applied in all cases. The methyl groups were allowed to rotate, but not to tip, to best fit the electron density. Full details of the structures and refinements are available in the deposited crystallographic information files.

Crystal data for **3**: $C_{13}H_{14}N_2O_2S$, $M_r = 262.32$, monoclinic, space group $P2_1$ (no. 4), $a = 11.2901$ (4) Å, $b = 6.0529$ (2) Å, $c = 18.8537$ (8) Å, $\beta = 98.753$ (3)°, $V = 1273.42$ (8) Å^3, $Z = 4$, $T = 100$ K, $\mu = 2.231$ mm^{-1}, $\rho_{calc} = 1.368$ g cm^{-3}, 9542 reflections measured ($8.6 \leqslant 2\theta \leqslant 141.2°$), $R(F) = 0.058$ [9086 reflections with $I > 2\sigma(I)$], $wR(F^2) = 0.173$ (all data), $\Delta\rho_{min,\ max}$ (e Å^{-3}) = –0.49, +0.29, Flack absolute structure parameter –0.034 (16), refined as a non-merohedral twin, Cambridge Crystallographic Data Center (CCDC) deposition number 2277285.

Crystal data for **4**: $C_{20}H_{20}N_2O_4S_2$, $M_r = 416.50$, orthorhombic, space group *Pccn* (no. 56), $a = 8.3251$ (4) Å, $b = 36.9411$ (18) Å, $c = 12.9160$ (7) Å, $V = 3972.2$ (3) Å^3, $Z = 8$, $T = 100$ K, $\mu = 2.681$ mm^{-1}, $\rho_{calc} = 1.393$ g cm^{-3}, 35539 reflections measured ($4.8 \leqslant 2\theta \leqslant 154.3°$), 4140 unique ($R_{Int} = 0.060$), $R(F) = 0.055$ [3695 reflections with $I > 2\sigma(I)$], $wR(F^2) = 0.136$ (all data), $\Delta\rho_{min,\ max}$ (e Å^{-3}) = –0.67, +0.39, CCDC deposition number 2277286.

Crystal data for **13**: $C_{27}H_{26}N_2O_6S_3$, $M_r = 570.68$, triclinic, space group $P\bar{1}$ (no. 2), $a = 8.70715$ (16) Å, $b = 16.4892$ (5) Å, $c = 19.2569$ (3) Å, $\alpha = 95.169$ (2)°, $\beta = 91.4000$ (15)°, $\gamma = 105.197$ (2)°, $V = 2653.93$ (11) Å^3, $Z = 4$, $T = 100$ K, $\mu = 2.943$ mm^{-1}, $\rho_{calc} = 1.428$ g cm^{-3}, 47498 reflections measured ($4.6 \leqslant 2\theta \leqslant 153.9°$), 10495 unique ($R_{Int} = 0.089$), $R(F) = 0.086$ [7617 reflections with $I > 2\sigma(I)$], $wR(F^2) = 0.243$ (all data), $\Delta\rho_{min,\ max}$ (e Å^{-3}) = –0.89, +1.42, CCDC deposition number 2277287.

Crystal data for **19**: $C_{31}H_{28}N_2O_6S_3$, $M_r = 620.73$, orthorhombic space group *Pbca* (no. 61), $a = 15.3534$ (1) Å, $b = 16.0086$ (1) Å, $c = 23.3294$ (1) Å, $V = 5734.05$ (6) Å^3, $Z = 8$, $T = 100$ K, $\mu = 2.774$ mm^{-1}, $\rho_{calc} = 1.438$ g cm^{-3}, 161236 reflections measured ($7.6 \leqslant 2\theta \leqslant 154.0°$), 5874 unique ($R_{Int} = 0.053$), $R(F) = 0.031$ [5710 reflections with $I > 2\sigma(I)$], $wR(F^2) = 0.083$ (all data), $\Delta\rho_{min,\ max}$ (e Å^{-3}) = –0.39, +0.40, CCDC deposition number 2277288.

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Supplemental material

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References

1. Fu S, Jiang H, Deng Y, et al. *Adv Synth Catal* 2011; 353: 2795–2804.
2. Rivillo D, Gulyas H, Benet-Buchholz Escudero-Adan EC, et al. *Angew Chem Int Ed* 2007; 46: 7247–7250.
3. Bondarenko NA. *Russ J Gen Chem* 1996; 66: 584–589.
4. Oloyede HO, Woods JAO, Gorls H, et al. *New J Chem* 2020; 44: 14849–14858.
5. Avdeenko AP. *Russ J Org Chem* 1998; 34: 515–524.
6. Saunders A and Sprake JM. *J Chem Soc C: Organic* 1970; 1161–1165.
7. Mertes MP and Lin AJ. *J Med Chem* 1970; 13: 7–81.
8. Wollenweber M, Keese R and Stoeckli-Evans H. *Zeitsch Natur, B: Chem Sci* 1998; 53: 145–148.
9. Plater MJ and Harrison WTA. *Chem Open* 2022; 11: e2021001501of4.
10. Plater MJ and Harrison WTA. *Chem Open* 2022; 11: e2022000921of7.
11. Squires C, Baxter CW, Campbell J, et al. *Dalton Trans* 2006; 2026–2034.
12. Tasker P, Parkin A, Squires C, et al. *CSD Commun* 2005; CCDC278226.
13. Groom CR, Bruno IJ, Lightfoot MP, et al. *Acta Cryst* 2016; B72: 171–179.
14. Ryu H-J, Yang S-J, Lee GH, et al. *ACS Comb Sci* 2018; 20: 282–291.
15. Basato M, Detomi N, Meneghetti M, et al. *Inorgan Chim Acta* 1999; 285: 18–24.
16. Sheldrick GM. *Acta Cryst* 2015; A7: 138.
17. Sheldrick GM. *Acta Cryst* 2015; C7: 138.
18. Scherowsky G. *J Liebigs Ann Chem* 1970; 739: 45–55.
19. Cheesman GWH. *J Chem Soc* 1955; 3308–3310.
20. Cheesman GWH. *J Chem Soc* 1955; 1804–1809.
21. Stetter H. *Chem Ber* 1953; 86: 161–167.
22. Sato K, Ogiwara Y and Sakai N. *Bull Chem Soc Jap* 2020; 93: 1595–1602.
23. Hodgson HH and Whitehurst JS. *J Chem Soc* 1945; 202–204.