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Reduction of Nitroarenes, Azoarenes and Hydrazine Derivatives by an Organic Super Electron Donor

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ABSTRACT

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Reduction of nitrobenzene by excess organic electron donor, 12, affords diphenylhydrazine in a reaction where azobenzene oxide and azobenzene are likely intermediates. No cleavage of the N-N σ-bond is seen under photoactivation conditions, whereas traces are seen under thermal activation. Hydrazone derivatives were prepared to explore the cleavage of N-N σ-bonds; the results show that a low-lying LUMO assists the transition state for accepting an electron, and the stabilisation that the potential fragments from N-N bond cleavage afford to the fragments is important in determining whether cleavage is observed.

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1. Introduction

Nitrobenzenes 1 are versatile substrates for synthesis, undergoing easy reduction to anilines 4 via monoaryl compounds 2-4, and/or compounds arising from the coupling of intermediates, 5-8.1,2 The reaction conditions and reagents are important in determining the products, as they provide reactive species at different rates and therefore different concentrations, which is important for coupling. In terms of closed-shell intermediates, nitroso compounds 2 can dimerise to form diazene dioxides 5 or can condense with hydroxylamines 3 to afford azoxides 6, or with anilines 4 to afford azo-compounds 7, while electron transfer-based reductions could also access these coupled compounds via radical intermediates. Further reduction to diarylhydrazines 8 can then follow.1

Scheme 1. Reduction of nitroarenes

Despite the extensive interest in reduction of nitro groups, no reduction of nitro groups in the absence of redox-active metals with organic electron donors has yet been recorded, although Hu et al.1 explored the reduction of nitrobenzenes to anilines 4 by electron transfer, using samarium and the organic mediator 1,1'-dioctyl-4,4'-bpyridinium dibromide.

Scheme 2. Preparation and reaction of electron donor 12.

Organic electron donors have been widely studied in recent years, and their ability to behave as strong reducing agents has been established.1,4,9 An easily accessible donor is DMAP-derived donor 12; this is prepared by treatment of the precursor salt 9 with two equivalents of base (Scheme 2). When it acts as a donor, sequential transfer of two electrons from 12 affords the aromatic disalt, 14. Compound 12 is deep purple in colour with an absorption maximum around 365 nm, making it convenient for photoactivated reactions without specialist photochemical equipment. This affords the opportunity for promotion of an electron from HOMO to LUMO. Photoexcited 12 is therefore even more reducing than the ground state counterpart.1,11 The experiments reported in this paper started by probing the reactivity of electron donor 12 with nitrobenzene under both photoactivated and thermal conditions.

2. Results

Nitrobenzene was treated with disalt 9, (X = I) and NaH as base under photoactivated conditions (365 nm) at ambient temperature as shown in Table 1 (entries 1-4). Full reduction from nitrobenzene to aniline requires 6 electrons (+ corresponding protons – see below); these could be provided by 3 equivalents of donor 12, which would require treatment of salt 9 (3 eq) with NaH (6 eq) as in entry 1. This experiment led to isolation of 1,2-diphenylhydrazine 18 cleanly, but to no aniline 19. Clearly, conditions were favourable for intermediates to couple. Progressively decreasing the amount of reducing agent reacted with substrate 15 allowed us to probe for potential intermediates en route to 18 and led to the results in Table 1 (entries 2-4). The results show that in the presence of limited equivalents of 9 (1 eq, entry 4), azoxide 16 (60%) is formed as the exclusive product. Increasing the number of equivalents of 9 to 1.5 gave rise to azobenzene 17 (68%), while a further increase in reducing equivalents yielded diphenylhydrazine 18. The presence of the DMAP-derived salt 9 was essential, as the same reaction run without the salt led to no reaction. These outcomes from the photoactivation conditions were compared with thermal activation (Table 1, entry 5) also using NaH (6 eq) and salt 9 (3 eq), which provided diphenylhydrazine 18 (45%) as the major product, together with azobenzene 17 (14%) and a small amount of aniline 19 (4%).

Table 1. Reduction of nitrobenzene by donor 12, formed in situ.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reduction of 15 as in scheme conditions (%)</th>
<th>16 (%)</th>
<th>17 (%)</th>
<th>18 (%)</th>
<th>19 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaH (6 eq), UV irradiation, rt, 9 (X = I), (3 eq)</td>
<td>0 0 84 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>NaH (4 eq), UV irradiation, rt, 9 (X = I), (2 eq)</td>
<td>0 23 59 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NaH (3 eq), UV irradiation, rt, 9 (X = I), (1.5 eq)</td>
<td>0 68 0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>NaH (2 eq), UV irradiation, rt, 9 (X = I), (1 eq)</td>
<td>60 &lt;1 0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>NaH (6 eq), 130 °C, 9 (X = I), (3 eq)</td>
<td>0 14 45 4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These results are consistent with the formation of 18 through a sequential series of reductions, with 16 and 17 as intermediates.

Table 2. Reduction of azoxybenzene 16 by donor 12, formed in situ

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reduction of 16 as in scheme conditions (%)</th>
<th>16 (%)</th>
<th>17 (%)</th>
<th>18 (%)</th>
<th>19 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaH (6 eq), UV irradiation, rt, 9 (X = I), (3 eq)</td>
<td>0 18 73 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>NaH (4 eq), UV irradiation, rt, 9 (X = I), (2 eq)</td>
<td>0 20 70 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NaH (2 eq), UV irradiation, rt, 9 (X = I), (1 eq)</td>
<td>0 80 5 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>NaH (6 eq), 130 °C, 9 (X = I), (3 eq)</td>
<td>0 82 traces 0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
To check whether this scheme was reasonable, the various individual products were tested for their reactivity. Firstly, azoxybenzene 16 was reacted with donor 12 formed in situ, according to the conditions shown in the experiments in Table 2 using precursor salt 9 in the presence of NaH. In the presence of excess of the reducing agent and under photochemical activation (Table 2, entries 1 and 2), azoxybenzene was reduced principally to hydrazobenzene 18, while azobenzene 17 was the minor product. When just 1 equivalent of the reducing agent 12 was present (entry 3), then azobenzene was the dominant product (80%), while a trace (5%) of hydrazobenzene was isolated. When the reaction was repeated with excess of reducing agent (entry 4), but under thermal rather than photochemical activation, azobenzene was the major product (82%).

To check that azobenzene 17 can be reduced to diphenylhydrazine 18 under the photoactivated conditions, it was subjected to the reaction in the presence of varying amounts of [disalt 9 + NaH], leading to uniformly high yields of 18 (Table 3, entries 1-3). In these reactions, formation of aniline 19 was not observed, even when there was an excess of electrons available. When the reduction of azobenzene 17 was conducted under thermal conditions, diphenylhydrazine 18 was again the major product, but aniline was produced in low yield (4%) consistent with thermal fragmentation of an N-N bond; perhaps in the dianion of 18. Although photoactivation leads to a more powerful reducing system than the thermal activation, this dianion of 18 should be very difficult to reduce, so that, in the absence of thermal fragmentation, further progress towards aniline 19 would rely on conversion of this dianion to a less negatively charged species (see below).

Table 3. Reduction of azobenzene 17

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reduction of 17 as in scheme conditions</th>
<th>Recovered 18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaH (6 eq), UV irradiation, rt, 9 (X = I), (3 eq)</td>
<td>0 89</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>NaH (4 eq), UV irradiation, rt, 9 (X = I), (2 eq)</td>
<td>0 90</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>NaH (2 eq), UV irradiation, rt, 9 (X = I), (1 eq)</td>
<td>8 79</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>NaH (6 eq), 130°C, 9 (X = I), (3 eq)</td>
<td>12 72</td>
<td>4</td>
</tr>
</tbody>
</table>

For formation of products 17, 18 from nitrobenzene, a coupling of two intermediates is needed, involving the formation of an N-N bond. Scheme 1 shows three steps at which dimerization could occur, and all involve nitrobenzene. At this stage, we do not know if all three ways of forming the N-N bond contribute to the product, or indeed if open-shell intermediates are active in the coupling. Besides the N-N bond formation, oxygen atoms must be removed to arrive at 17 and 18. Scheme 3 shows two ways in which products arising from the electron donor 12 can assist. The first deals with protonation. Under our conditions, just sufficient NaH is used to deprotonate 9 and form 12; when donor 12 transfers two electrons, dication 14 is formed, featuring somewhat acidic protons, ortho to the pyridinium nitrogen. Dianion 20, a likely intermediate in the reduction of nitrobenzene, could be protonated to 21, which would then collapse to nitrosobenzene. A similar proton transfer could occur, employing radical cation 13 (the structure is shown in Scheme 2) rather than dication 14.

Alternatively, rather than being deprotonated, intermediates 13 and/or 14 could be attacked by nucleophiles in the position ortho to the pyridine nitrogen. In this case, dianion 20 would afford 23, fragmentation of which could yield nitrosobenzene 22. Scheme 3 shows dianion 20 as the reactive intermediate, but analogous solutions could be proposed for any negatively charged intermediate that needs to shed a leaving group.

Scheme 3. Possible routes for oxygen atom removal

In our experiments above, no N-N σ-bond cleavage was observed by electron donor 12 at ambient temperature under photoactivated conditions. An area of great current interest involves reducing molecular nitrogen to ammonia with electron donors; the first steps would involve reduction of the π-bonds, but a really challenging part of the process would involve cleavage of the N-N σ-bond of hydrazine or a derivative. Accordingly, we determined to understand whether N-N σ-bonds were intrinsically too difficult to cleave, and to what extent their cleavage is facilitated by substituents. In the experiments above, cleavage might have been impeded due to charge (e.g. in reduction of 17, we would expect the dianion of 18 to form, but further reduction of that charged derivative leading to N-N bond cleavage would likely be impossible due to the charge; this charge could potentially be mitigated through either of the processes in Scheme 3, employing the dianion 18 as reactive intermediate instead of 20).

The fact that N-N σ-bond cleavage was not seen following activation by our photoactivated donor 12 now led us to explore the factors that might influence cleavage of such bonds. Accordingly, we prepared a series of hydrazine derivatives 24-27. Reduction of these compounds should be assisted if a low energy π* or σ* orbital is available to house an electron from the electron donor. Following acceptance of an electron, cleavage of the N-N bond in the radical anion would be facilitated by substituents on the N atoms that would stabilise the resulting fragments, the radical and the anion. Hence the easiest of our substrates to cleave should be the tetraphenylhydrazine 24.

Indeed, it is seen that 24 was reductively cleaved to afford diphenylamine 28 in excellent yield under either photochemical or thermal activation (entries 1 and 2 respectively). Substrate 25 still should have a low-lying LUMO associated with the diphenylaminogroup; however, the cleavage of a radical anion of this substrate should be more challenging than in the radical anion of 24, as the resulting piperidonyl anion or radical will be less stabilised than the corresponding diphenylaminyl species from 24. This was borne out by experiment - substantial amounts of starting material were recovered under both photoactivation and thermal activation, but a greater amount of recovered starting material was seen in the thermal activation case (87% vs. 56%); correspondingly, whereas 28 was isolated, albeit in low yield (35%) from the photoactivation, the thermal activation afforded no such product. Compound 26 underwent cleavage to afford a low yield of diphenylamine (18%) under our standard photoactivation conditions (18 h). It is noteworthy that extending the time of the photoactivation for 25 and 26 to 36 h, did not lead to increased yields over the shorter duration experiments.
Table 4. Reduction of hydrazines and derivatives

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions (in salt, (n, k = 1))</th>
<th>Substrate</th>
<th>Recovered substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaH (6 eq), UV irradiation, rt, 9, [3 eq]</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>NaH (6 eq), 130°C, 9, [3 eq]</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>NaH (6 eq), UV irradiation, rt, 9, [3 eq] 18 h</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>NaH (6 eq), 130°C, 9, [3 eq] 18 h</td>
<td>25</td>
<td>87</td>
</tr>
<tr>
<td>5</td>
<td>NaH (6 eq), UV irradiation, rt, 9, [3 eq] 18 h</td>
<td>26</td>
<td>66</td>
</tr>
<tr>
<td>6</td>
<td>NaH (6 eq), 130°C, 9, [3 eq]</td>
<td>26</td>
<td>94</td>
</tr>
<tr>
<td>7</td>
<td>NaH (6 eq), UV irradiation, rt, 9, [3 eq] 36 h</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td>8</td>
<td>NaH (6 eq), UV irradiation, rt, 9, [3 eq] 36 h</td>
<td>26</td>
<td>53</td>
</tr>
<tr>
<td>9</td>
<td>NaH (12 eq), UV irradiation, rt, 9, [6 eq] 18 h</td>
<td>25</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>NaH (12 eq), UV irradiation, rt, 9, [6 eq] 18 h</td>
<td>26</td>
<td>65</td>
</tr>
<tr>
<td>11</td>
<td>NaH (6 eq), UV irradiation, rt, 9, [3 eq] 18 h</td>
<td>27</td>
<td>70</td>
</tr>
<tr>
<td>12</td>
<td>NaH (6 eq), 130°C, 9, [3 eq]</td>
<td>27</td>
<td>70</td>
</tr>
</tbody>
</table>

Similarly, increasing the number of equivalents of electron donor to six, had no effect on the outcome of the photoactivation reactions of 25 and 26. [Piperidine or piperidinone respectively, were not isolated from these reactions. Performing repeat experiments in which defined amounts of piperidine and piperidinone were added just prior to workup also did not lead to their isolation; we attribute this to volatility and water solubility].

3. Conclusions

Reduction of nitrobenzene by sufficient numbers of equivalents of organic electron donor, 12, affords diphenylhydrazine; less equivalents of reducing agent afford azobenzene oxide or azobenzene. No cleavage of the N-N σ-bond is seen under photoactivation conditions, whereas traces are seen under thermal activation. Efforts to cleave N-N σ-bonds in hydrazine derivatives show that a low-lying LUMO can assist the transition state for accepting an electron, and the structure of the potential fragments from N-N bond cleavage affects that cleavage.

4. Experimental section

4.1. General Information

All reagents were commercially available and used without additional purification.\(^1\)H NMR and \(^{13}\)C NMR spectra were recorded in CDCl\(_3\) as solvent on a Bruker AV3 at 400 and 100 MHz, respectively, and the NMR chemical shifts are reported in ppm downfield from an internal solvent peak. Signal multiplicities are abbreviated as: s, singlet; d, doublet; t, triplet; q, quartet; quint, quintuplet; m, multiplet; bs, broad singlet; tt, triplet of triplets. Coupling constants are given in Hertz (Hz).

Thin layer chromatography (TLC) was performed using aluminium-backed sheets of silica gel and visualized under a UV lamp (254 nm). TLCs were revealed with phosphomolybdic acid. Column chromatography was performed to purify compounds by using silica gel 60 (200–400 mesh).

The electron transfer reactions were carried out within a glove box (Innovative Technology Inc., USA) under nitrogen atmosphere. All solvents or samples introduced into the glovebox were transferred through the port, which was evacuated and purged with nitrogen ten times before entry. When the reaction mixtures were prepared, the reaction vessel was removed from the glovebox and the rest of the reaction was performed in a fume hood under UV radiation or thermal conditions. All the UV reactions were carried out by using two focused UV lamps with filters (\(\lambda = 365\) nm, each 100 watts) placed opposite to each other, around the Pyrex reaction flask, at room temperature. Infra-Red spectra were recorded on an ATR-IR spectrometer. Melting points were determined on a Gallenkamp Melting point apparatus. High-resolution mass spectrometry (HRMS) was performed at Swansea University, in the EPSRC National Mass Spectrometry Centre. Accurate mass was obtained using atmospheric pressure chemical ionization (APCI), chemical ionisation (CI), electron ionisation (EI), electrospray ionisation (ESI) or nanospray ionisation (NSI) with a LTQ Orbitrap XL mass spectrometer.

4.2 Synthesis of hydrazine derivatives

4.1.1. Tetraphenylhydrazine (24)\(^{6}\)

To a 250 mL 3-necked round-bottomed flask, under argon, were added copper chloride 745 (1.98 g, 20.0 mmol) and pyridine (50 mL). The atmosphere of the flask was replaced by oxygen and a solution of diphenylamine 744 (1.69 g, 9.99 mmol) in pyridine (10 mL) was added to the flask upon vigorous stirring.

![Chemical structure of tetraphenylhydrazine (24)]
and oxygen flow. After addition, the mixture was stirred at room temperature for 21 h under oxygen atmosphere. Pyridine was removed by distillation and the resulting residue was extracted with Et₂O (4 x 25 mL), the combined organic extracts were dried over Na₂SO₄, filtered and concentrated to afford the crude product. Purification was made by column chromatography on silica using DCM (25%) in hexane to afford tetraphenylhydrazide 24 as a white powder (184.9 mg, 0.55 mmol, 11%). M. Pt. 144–146 °C (lit. 144–147 °C) δH (400 MHz, CDCl₃): 6.90 (4H, t, J = 7.2, 1.2 Hz, ArHf), 7.22-7.17 (8H, m, ArHf), 7.32-7.29 (8H, m, ArHf), δC (100 MHz, CDCl₃): 118.3, 122.2, 129.2, 143.7. IR (NEAT) ν (cm⁻¹) = 689, 740, 1030, 1273, 1294, 1485, 1586. m/z (APCI) calcd. for C₃₉H₃₂N₈ [M+H⁺]: 537.1699, found: 537.1696.

4.1.2. 1-(Diphenylamino)piperidin-2-one (25)

To a 50 mL round-bottomed flask at 0 °C, N,N-diphenylhydrazide 24 (500 mg, 2.72 mmol), CH₂Cl₂ (10 mL) and a solution of Na₂CO₃ (10 % in water, 10 mL) was added. After stirring for 5 min, 5-chlorovaleroylchlorethymine (545 mg, 3.54 mmol) was added dropwise to the mixture. The reaction mixture was stirred and allowed to warm from 0 °C to room temperature overnight. The mixture was extracted with CH₂Cl₂ (4 x 15 mL), the combined organic extracts were washed once with water, dried over Na₂SO₄, filtered and concentrated to afford the crude product. Purification was made by column chromatography on silica using EtOAc (10 %) in hexane to afford 1-chloro-N,N-diphenyl-piperidine 25 (240 mg, 0.90 mmol) and dry diethyl ether (20 mL) were added to a 100 mL 3-necked round-bottomed flask under argon. The reaction mixture was refluxed at 35 °C overnight. Then LiAlH₄ was cautiously quenched by addition of isopropanol and then water. The precipitate was filtered off and the filtrate was washed twice with water, dried over Na₂SO₄, filtered and concentrated to afford the crude product. Purification was made by column chromatography on silica eluting with EtOAc (2 %) in hexane to afford 1-N,N-diphenylaminopiperidine 26 a white solid (170 mg, 0.67 mmol, 75 %). M. Pt. 55 – 57 °C δH (400 MHz, CDCl₃): 1.33 (2H, quint. J = 6.0 Hz, CH₂), 1.75 (4H, quint., J = 5.6 Hz, 2 × CH₂), 2.69 (4H, t, J = 5.2 Hz, 2 × CH₂), 7.04-7.09 (6H, m, ArH), 7.28-7.34 (4H, m, ArH), δC (100 MHz, CDCl₃): 23.2, 26.1, 52.6, 121.7, 122.0, 128.4, 143.9. IR (NEAT) ν (cm⁻¹) = 690, 748, 866, 1314, 1443, 1487, 1585, 2938. HRMS (CI): calcd. for C₂₄H₂₁N₂ [M+H⁺]: 337.1699, found: 337.1702.

4.1.4. Bipiperidine (27)ᵇ

Piperidine (2.5 g, 29.4 mmol), NaOH (2.35 g, 58.8 mmol), H₂O (15 mL) and AgNO₃ (250.0 mg, 1.47 mmol), were added to a 100 mL round-bottomed flask at 0 °C. After stirring for 15 min, a solution of Na₂S₂O₄ (6.99 g, 29.4 mmol) in H₂O (20 mL) was added to the mixture which was then stirred from 0 °C to room temperature for 4 h. The mixture was extracted with EtOAc (3 x 30 mL), the combined organic extracts were dried over Na₂SO₄, filtered and concentrated. The crude product was purified by column chromatography on silica eluting with EtOAc (10 %) in hexane to afford bipiperidine 27 as a yellow oil (1.29 g, 7.64 mmol, 52 %). δH (400 MHz, CDCl₃): 1.34 (4H, m, CH₂), 1.59 (8H, m, CH₂), 2.60 (8H, t, J = 6.0 Hz, CH₂), δC (100 MHz, CDCl₃): 24.9, 26.7, 49.3. IR (NEAT) ν (cm⁻¹) = 875, 1422, 2731, 2800, 2852, 2930. m/z (EI) C₁₁H₁₄NO₂ [M]: 168.1.

4.2. General reduction procedures

Inside a glovebox under nitrogen atmosphere, a pressure tube was loaded with DMAP salt (specified amount), dry DMF (5 mL), NaH (specified amount) and reduction substrate (0.33 mmol). The tube was sealed, taken outside the glovebox and the mixture was stirred for 18 h at room temperature under UV light OR at 130 °C without UV light, as indicated. The mixture was quenched at room temperature with water (30 mL), extracted
with EtO (2 x 25 mL), the combined organic extracts were washed with water (3 x 25 mL), dried over Na₂SO₄, filtered and concentrated. Crude products were purified by column chromatography on silica eluting with EtOAc (5%) in hexane, for isolation of azobenzene 17, azoxybenzene 16 and diphenylamine 28, and with EtOAc (20%) in hexane for isolation of hydrazine 18.

4.2.1. Reduction of nitrobenzene 15

4.2.1.1. Table 1, Entry 1.

Nitrobenzene 15 (41 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford, following work-up and chromatography, 1,2-diphenylhydrazine 18 as a white solid (25.8 mg, 0.14 mmol, 84%). M.P. 123–125 °C (lit. 124–125 °C) δ(400 MHz, CDCl₃): 5.62 (2H, bs, NAr), 6.87–6.82 (6H, m, ArH). δC (100 MHz, CDCl₃): 112.5, 120.1, 129.5, 149.0. IR (NEAT) ν (cm⁻¹): 689, 775, 927, 1072, 1454, 1483. m/z (NSI) calecd for C₁₇H₁₁N₂O: [M⁺]: 285.073; found: 285.073.

4.2.1.2. Table 1, Entry 2.

Nitrobenzene 15 (41 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford azobenzene 17 (17.9 mg, 0.10 mmol, 59%). NMR spectra details as above, and azobenzene 17 as an orange solid (6.9 mg, 0.04 mmol, 23%). M. Pt. 65–66 °C (lit. 65–66 °C) δ(400 MHz, CDCl₃): 7.55–7.46 (6H, m, ArH). IR (NEAT) ν (cm⁻¹): 1320, 129.2, 131.1, 152.8. IR (NEAT) ν (cm⁻¹): 688, 775, 927, 1072, 1454, 1483. m/z (EI) C₁₇H₁₇N₂: [M⁺]: 281.1.

4.2.1.3. Table 1, Entry 3.

Nitrobenzene 15 (41 mg, 0.33 mmol) was treated with DMAP salt 9 (267.4 mg, 0.50 mmol) and sodium hydride (23.8 mg, 0.99 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford azobenzene 17 (20.4 mg, 0.11 mmol, 68%). NMR spectra details as above.

4.2.1.4. Table 1, Entry 4.

Nitrobenzene 15 (41 mg, 0.33 mmol) was treated with DMAP salt 9 (178.3 mg, 0.33 mmol) and sodium hydride (15.8 mg, 0.66 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford azobenzene 16 (a yellow oil (19.6 mg, 0.10 mmol, 60%). δ(400 MHz, CDCl₃): 7.39 (1H, t, J = 6.8, 1.2 Hz, ArH), 7.59–7.47 (5H, m, ArH). δC (100 MHz, CDCl₃): 122.5, 125.7, 128.9, 129.0, 129.8, 131.7, 144.2, 148.5. IR (NEAT) ν (cm⁻¹): 686, 764, 1277, 1301, 1441, 1476. m/z (NSI) calecd for C₁₇H₁₇N₂O: [M⁺]: 215.0866; found: 215.0865. A trace amount of azobenzene 17 was also observed in the ¹H NMR spectra of the crude product.

4.2.1.5. Table 1, Entry 5.

Nitrobenzene 15 (40.6 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at 130 °C for 18 h to afford azobenzene 17 (3.3 mg, 0.02 mmol, 11%), 1,2-diphenylhydrazine 18 (13.7 mg, 0.07 mmol, 45%), NMR spectra details as above, and aniline 19 (1.2 mg, 0.01 mmol, 4%), yields were quantified by use of 1,3,5-trimethoxybenzene as an internal NMR standard. Observed ¹H NMR for aniline 19: δ(400 MHz, CDCl₃): 3.05 (2H, s, NH₂), 6.70–6.77 (2H, m, ArH). δC (100 MHz, CDCl₃): 171.7–17.13 (2H, m, ArH), 7.13–7.13 (2H, m, ArH); data were in accordance with literature.

4.2.2. Reduction of azobenzene 16

4.2.2.1. Table 2, Entry 1.

Azobenzene 16 (65.4 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford azobenzene 17 (11 mg, 0.06 mmol, 18%) and 1,2-diphenylhydrazine 18 (44 mg, 0.24 mmol, 73%). NMR spectra details as above.

4.2.2.2. Table 2, Entry 2.

Azobenzene 16 (65.4 mg, 0.33 mmol) was treated with DMAP salt 9 (356.6 mg, 0.66 mmol) and sodium hydride (31.7 mg, 1.32 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford azobenzene 17 (12 mg, 0.066 mmol, 20%) and 1,2-diphenylhydrazine 18 (42.5 mg, 0.23 mmol, 70%). NMR spectra details as above.

4.2.2.3. Table 2, Entry 3.

Azobenzene 16 (65.4 mg, 0.33 mmol) was treated with DMAP salt 9 (178.3 mg, 0.33 mmol) and sodium hydride (15.8 mg, 0.66 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford azobenzene 17 (48 mg, 0.26 mmol, 80%) and 1,2-diphenylhydrazine 18 (3 mg, 0.017 mmol, 5%). NMR spectra details as above.

4.2.2.4. Table 2, Entry 4.

Azobenzene 16 (65.4 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at 130 °C for 18 h to afford azobenzene 17 (49 mg, 0.27 mmol, 82%) and traces of 1,2-diphenylhydrazine 18. NMR spectra details as above.

4.2.3. Reduction of azobenzene 17

4.2.3.1. Table 3, Entry 1.

Azobenzene 17 (60.1 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford 1,2-diphenylhydrazine 18 (54.1 mg, 0.29 mmol, 89%). NMR spectra details as above.

4.2.3.2. Table 3, Entry 2.

Azobenzene 17 (60.1 mg, 0.33 mmol) was treated with DMAP salt 9 (356.6 mg, 0.66 mmol) and sodium hydride (31.7 mg, 1.32 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford 1,2-diphenylhydrazine 18 (54.1 mg, 0.30 mmol, 90%). NMR spectra details as above.
mg, 0.66 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h to afford 1,2-diphenylhydrazine 18 (48.0 mg, 0.26 mmol, 79%) and remaining starting material 17 (4.8 mg, 0.026 mmol, 8%). NMR spectra details as above.

4.2.3.4. Table 3, Entry 4.

Azobenzene 17 (60.1 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at 130 °C for 18 h to afford remaining starting material 17 (7.2 mg, 0.04 mmol, 12%), 1,2-diphenylhydrazine 18 (43.8 mg, 0.24 mmol, 72%) and aniline 19 (2.5 mg, 0.026 mmol, 4%). NMR spectra details as above.

4.2.4. Reduction of hydrazine derivatives 24 – 27

4.2.4.1. Table 4, Entry 1.

Tetraphenylhydrazine 24 (111.0 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h. The crude product was purified by column chromatography on silica eluting with EtOAc (7%) in hexane to afford diphenylamine 28 as an off-white solid (87.1 mg, 0.51 mmol, 78%). M. Pt. 51-53 °C (lit. 52-54 °C). ¹H (400 MHz, CDCl₃): 6.93 (2H, tt, J = 7.6, 0.8 Hz, ArH), 7.09-7.06 (4H, m, ArH), 7.29-7.24 (4H, m, ArH), 118.0, 121.2, 129.5, 143.3. IR (NEAT) ν (cm⁻¹) = 689, 743, 877, 1175, 1318, 1495, 1515, 1589, 3382. m/z (EI) C₉H₁₈N [M⁺]: 169.1.

4.2.4.2. Table 4, Entry 2.

Tetraphenylhydrazine 24 (111.0 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at 130 °C for 18 h to afford diphenylamine 9 (54 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (3 mL) at room temperature under UV light for 36 h. The crude product was purified by column chromatography on silica using EtOAc (5%) in hexane to afford diphenylamine 28 (14 mg, 0.083 mmol, 40%). NMR spectra details as above.

4.2.4.3. Table 4, Entry 3.

1-(Diphenylamino)piperidine 26 (54 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (3 mL) at 130 °C for 18 h. The crude product was purified by column chromatography on silica eluting with EtOAc (5%) in hexane to afford diphenylamine 28 (12 mg, 0.071 mmol, 35%). NMR spectra details as above.

4.2.4.4. Table 4, Entry 4.

1-(Diphenylamino)piperidin-2-one 25 (54 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (3 mL) at room temperature under UV light for 18 h. The crude product was purified by column chromatography on silica eluting with EtOAc (5%) in hexane to afford diphenylamine 28 (12 mg, 0.071 mmol, 35%). NMR spectra details as above.

4.2.4.5. Table 4, Entry 5.

1-(Diphenylamino)piperidine 26 (50 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (3 mL) at room temperature under UV light for 18 h. The crude product was purified by column chromatography on silica using EtOAc (2%) in hexane to afford diphenylamine 28 (6 mg, 0.036 mmol, 18%). NMR spectra details as above.

4.2.4.6. Table 4, Entry 6.

1-(Diphenylamino)piperidine 26 (54 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (3 mL) at 130 °C for 18 h. ¹H-NMR of the crude product showed only remaining starting material (47 mg, 0.17 mmol, 94%).

4.2.4.7. Table 4, Entry 7.

1-(diphenylamino)piperidin-2-one 25 (54 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (3 mL) at room temperature under UV light for 36 h. The crude product was purified by column chromatography on silica using EtOAc (5%) in hexane to afford diphenylamine 28 (14 mg, 0.083 mmol, 40%). NMR spectra details as above.

4.2.4.8. Table 4, Entry 8.

1-(diphenylamino)piperidine 26 (50 mg, 0.20 mmol) was treated with DMAP salt 9 (324 mg, 0.60 mmol) and sodium hydride (29 mg, 1.20 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h. The crude product was purified by column chromatography on silica using EtOAc (5%) in hexane to afford diphenylamine 28 (12.3 mg, 0.073 mmol, 36%). NMR spectra details as above.

4.2.4.9. Table 4, Entry 9.

1-(Diphenylamino)piperidin-2-one 25 (54 mg, 0.20 mmol) was treated with DMAP salt 9 (648 mg, 1.20 mmol) and sodium hydride (58 mg, 2.40 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h. The crude product was purified by column chromatography on silica using EtOAc (5%) in hexane to afford diphenylamine 28 (7.7 mg, 0.045 mmol, 23%). NMR spectra details as above.

4.2.4.10. Table 4, Entry 10.

1-(Diphenylamino)piperidine 26 (50 mg, 0.20 mmol) was treated with DMAP salt 9 (648 mg, 1.20 mmol) and sodium hydride (58 mg, 2.40 mmol) in dry DMF (5 mL) at room temperature under UV light for 18 h. ¹H-NMR of the crude reaction mixture showed only remaining starting material (38.9 mg, 0.23 mmol, 70%), yield was quantified by use of 1,3,5-trimethoxybenzene as an internal NMR standard.

4.2.4.11. Table 4, Entry 11.

Bipiperidine 27 (55.5 mg, 0.33 mmol) was treated with DMAP salt 9 (540.2 mg, 1.0 mmol) and sodium hydride (48.0 mg, 2.0 mmol) in dry DMF (5 mL) at 130 °C for 18 h. ¹H-NMR of the crude product showed only remaining starting material (38.9 mg, 0.23 mmol, 70%), yield was quantified by use of 1,3,5-trimethoxybenzene as an internal standard.

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References and notes

During revision of this paper, we note the following elegant references and notes.


