Facile Metal Free Regioselective Transfer Hydrogenation of Polarized Olefins with Ammonia Borane

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Supplementary Information for

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S1 General procedure: All the manipulations were carried out under a nitrogen atmosphere using Schlenk techniques or in a drybox (Model MB-150B-G). Reagent grade benzene, toluene, hexane, diethyl ether, and tetrahydrofuran were dried and distilled from sodium benzenophenone ketyl prior to use. Acetonitrile was distilled from CaH₂, and chloroform was dried by P₂O₅. NMR spectra were measured on a Varian Mercury spectrometer at 200 MHz for ¹H and 50.3 MHz for ¹³C{¹H}, Varian Gemini-2000 spectrometer at 300.1 MHz for ¹H, 64.2 MHz for ¹¹B{¹H} and 75.4 MHz for ¹³C{¹H} and on a Bruker-DRX-500 spectrometer at 500.2 MHz for ¹H, 107 MHz for ¹¹B{¹H} and 125.8 MHz for ¹³C{¹H}. Chemical shifts for ¹H and ¹³C are given in ppm relative to TMS and those for ¹¹B relative to Et₂O·BF₃.

S2 Synthesis of starting materials.
a) Ammonia-borane (AB) and deuterated AB’s:
BD₃NH₃: NaBD₄ (126.6 mg), (NH₄)₂CO₃ (325.8 mg) and dry THF (5 mL) were added to a Young-Schlenk tube. The mixture was then heated with stirring at 40 °C for 24 h. The resulting mixture was diluted with additional THF and filtered. The filtrate was evaporated and the prepared crude BD₃NH₃ was sublimed at 60 °C under vacuum for purification. AB can be prepared from NaBH₄ in the same way. BH₃ND₃ was prepared by dissolving AB in D₂O and stripping off the D₂O under vacuum at room temperature, this procedure was repeated three times. BD₃ND₃ was prepared from BD₃NH₃ using this method. Formation of deuterated AB adducts were confirmed by IR, ¹H, ²H and ¹¹B NMR spectra.

BD₃NH₃: δ₁H (ppm; 300 MHz; THF-D₈) 3.84 (t, J = 48.5 Hz, NH₃); δ₁D (ppm; THF) 1.29 (br, B-D₃); δ₁B (ppm; 64.2 MHz; THF-D₈ -22.5 (s, BD₃); IR (ATR): ν = 3307 (N-H), 2340 (B-H residue), 1741, 1657, 1376, 1292, 1095.

BH₃ND₃: δ₁H (ppm; 300 MHz; THF-D₈) 1.48 (q, J = 93Hz, BH₃); δ₁D (ppm; THF) 3.90 (s, N-D₃); δ₁B (ppm; 64.2 MHz; THF-D₈) -22.5 (q, J = 95.1 Hz, BH₃); IR (ATR): ν = 3298 (N-H residue), 2474, 2304 (B-H), 2271, 2151, 1154, 1064.

BD₃ND₃: δ₁D (ppm; THF) 1.29 (br, B-D₃), 3.89 (s, N-D₃); δ₁B (ppm; 64.2 MHz; THF-D₈) -22.5 (s, BD₃); IR (ATR): ν = 3289 (NH-residue), 2473, 2340 (BH-residue), 1714, 1165, 1064.

b) Preparation of polarized olefins:
All the polarized olefins were prepared with readily available materials.
Procedure A: A ketone (0.1 mol), malononitrile (0.2 mol), ammonium acetate (1.5 g), acetic acid (4.8 g) and benzene (30 mL) are refluxed with a Dean-Stark trap over night or until water production ceases (> 6 h). The mixture was then washed with water (3 × 30 mL)
and half saturated aqueous sodium chloride (1 x 30 mL) and then dried with magnesium sulfate. Then benzene was removed and the remaining liquid distilled under reduced pressure (for solid recrystallization). Olefins 1a-1f were obtained with 50-70% yield use this method.

2-Cyclohexylidenemalononitrile (1a), colorless liquid: \( \delta_H \) (ppm; 300 MHz; THF-D8) 1.63-1.74 (m, 2 H, -CH\(_2\)-), 1.74-1.87 (m, 4 H, -CH\(_2\)-), 2.62-2.75 (m, 4 H, -CH\(_2\)-); \( \delta_C \) (ppm; 75.4 MHz; THF-D8) 24.83, 27.52, 34.14, 82.61 (1 C, -C=), 112.03 (2 C, -CN), 183.89 (1 C, -C=).

Methyl 2-cyano-2-cyclohexylideneacetate (1b), colorless liquid: \( \delta_H \) (ppm; 300 MHz; CD\(_3\)CN) 1.57-1.83 (m, 6 H, -CH\(_2\)-), 2.59-2.65 (m, 2 H, -CH\(_2\)-), 2.91-2.97 (m, 2 H, -CH\(_2\)-), 3.76 (s, 3 H, -Me); \( \delta_C \) (ppm; 75.4 MHz; CD\(_3\)CN) 26.20, 28.98, 29.30, 32.22, 37.51, 53.13, 102.15 (1 C, -C=), 116.53 (1 C, -CN), 163.41 (1 C, -C=O), 181.63 (1 C, -C=).

2-Cyclopentylidenemalononitrile (1c), colorless liquid: \( \delta_H \) (ppm; 300 MHz; THF-D8) 1.86-1.95 (m, 4 H, -CH\(_2\)-), 2.75-2.87 (m, 4 H, -CH\(_2\)-); \( \delta_C \) (ppm; 75.4 MHz; C\(_6\)D\(_6\)) 25.61, 35.44, 81.25 (1 C, -C=), 112.21 (2 C, -CN), 191.71 (1 C, -C=).

2-(Propan-2-ylidene)malononitrile (1d), colorless liquid: \( \delta_H \) (ppm; 300 MHz; THF-D8) 2.30 (s, 6 H, -Me); \( \delta_C \) (ppm; 75.4 MHz; C\(_6\)D\(_6\)) 23.34, 86.09 (1 C, -C=), 112.22 (2 C, -CN), 178.01 (1 C, -C=).

2-(3,3-Dimethylbutan-2-ylidene)malononitrile (1e), colorless liquid: \( \delta_H \) (ppm; 300 MHz; CD\(_3\)CN) 1.33 (s, 9 H, -Me), 2.29 (s, 3 H, Me); \( \delta_C \) (ppm; 75.4 MHz; CD\(_3\)CN) 23.27, 28.88, 40.14, 84.80 (1 C, -C=), 114.51 (1 C, -CN), 114.74 (1 C, -CN), 191.59 (1 C, -C=).

2-(1-Phenylpropylidene)malononitrile (1f), white solid: \( \delta_H \) (ppm; 300 MHz; CD\(_3\)CN) 1.01 (t, \( J = 7 \) Hz, 3 H, -Me), 2.96 (q, \( J = 7 \) Hz, 2 H, -CH\(_2\)-), 7.47-7.48 (m, 5 H, -CH=); \( \delta_C \) (ppm; 75.4 MHz; CD\(_3\)CN) 12.65, 31.95, 85.26 (1 C, -C=), 113.65 (1 C, -CN), 114.12 (1 C, -CN), 128.53, 129.92, 132.60, 136.03, 183.11 (1 C, -C=).

Procedure B:³ To a stirred solution of 0.01 mol of aldehyde in 0.01 mol of malononitrile (or methylcyanoacetate) was added 3 g of alumina Merck 90. The reaction was exothermic. After 5 min, the product was extracted with dichloromethane (2 x 20 ml). The solvent was then removed, leaving a product of a good purity. Generally, the purification was not necessary. Olefin 1i and 1j were prepared by this method with nearly 100% yield.

2-Benzylidenemalononitrile (1i), slightly pink solid: \( \delta_H \) (ppm; 300 MHz; CD\(_3\)CN) 7.53-7.67 (m, 3 H, -CH=), 7.90 (m, 2 H, -CH=), 8.05 (s, 1 H, -CH=); \( \delta_C \) (ppm; 75.4 MHz; CD\(_3\)CN) 83.34 (1 C, -C=), 113.95 (1 C, -CN), 115.01 (1 C, -CN), 130.47, 131.47, 132.27, 135.28, 161.89 (1 C, -C=).
(E)-Methyl 2-cyano-3-phenylacrylate (1j), white solid: $\delta_H$ (ppm; 300 MHz; C$_6$D$_6$) 3.29 (s, 3 H, -Me), 6.85-6.93 (m, 3 H, -CH=), 7.58-7.61 (m, 2 H, -CH=), 7.94 (s, 1 H, -CH=); $\delta_C$ (ppm; 75.4 MHz; C$_6$D$_6$) 52.65, 103.20 (1 C, -C=), 115.59 (1 C, -CN), 129.10, 131.07, 131.77, 132.91, 154.56 (1 C, -C=O), 162.75 (1 C, -C=).

Other olefins were prepared using various other methods, respectively.

2-(Diphenylmethylene)malononitrile (1g): A 1 : 1 mixture of malononitrile and diphenylmethanimine was stirred without solvent at room temperature for 5 minutes giving the target product with nearly 100% yield. White solid: $\delta_H$ (ppm; 300 MHz; THF-D$_8$) 7.49-7.63 (m); $\delta_C$ (ppm; 300 MHz; THF-D$_8$) 114.67 (2 C, -CN), 129.58, 131.30, 133.11, 137.57, 174.59.

2-(9H-Fluoren-9-ylidene)malononitrile (1h) was prepared by melting and stirring of a 1:1 mixture of malononitrile and 9-fluoronone without solvent for 5 min, nearly 100% yield was obtained. Orange-red solid: $\delta_H$ (ppm; 300 MHz; THF-D$_8$) 7.36-7.42 (m, 2 H, -CH=), 7.53-7.59 (m, 2 H, -CH=), 7.70-7.75 (m, 2 H, -CH=), 8.35-8.39 (m, 2 H, -CH=); $\delta_C$ (ppm; 300 MHz; THF-D$_8$) 114.24 (2 C, -CN), 121.85, 127.30, 127.40, 130.03, 135.50, 143.32, 161.38.

Dimethyl 2-benzylidenemalonate (1k): A solution of benzaldehyde (1.01 mL, 10 mmol) in dry DMSO (5 mL) with 10% of proline (345 mg) was stirred for 5 min. Then dimethylmalonate (1.14 mL, 10 mmol) was added and the mixture was stirred at room temperature overnight. The reaction was diluted with AcOEt (30 mL) and washed twice with water (30 mL). The organic layer was dried over Na$_2$SO$_4$ and the solvent was removed in vacuo to afford the targeted product as colorless liquid with 52% yield. Colorless liquid: $\delta_H$ (ppm; 300 MHz; CD$_3$CN) 3.79 (s, 3 H, -Me), 3.80 (s, 3 H, -Me), 7.44 (s, 5 H, -CH=), 7.75 (s, 1 H, -CH=); $\delta_C$ (ppm; 75.4 MHz; CD$_3$CN) 53.29, 53.33, 126.79, 130.00, 130.25, 131.80, 133.66, 143.08, 165.18 (1 C, -C=O), 167.79 (1 C, -C=O).

S3 Typical transfer hydrogenation procedure.

In a glove-box, a 0.5 mm Young NMR tube was charged with olefin (0.1 mmol, for Pseudo-first order conditions 0.5 mmol), AB (0.1 mmol) and dry THF-D$_8$ or CD$_3$CN (0.6 mL). The tube was sealed with the screw cap and then lay at room temperature after shaking. The reaction was monitored by $^1$H NMR every several minutes (depends on the reaction rate). The typical resonance of the starting materials decreased, and a new signal of the saturated products gradually appeared. The disappearance of starting material indicating that the transformation was completed and $^{13}$C and $^{11}$B NMR spectra were then recorded. Finally the reaction mixture was diluted for analysis on GC-MS. Samples for low temperature NMR
were prepared at room temperature using chilled solvents, and immediately put into low temperature fridges until taken for NMR. All the reactions were carried out at least twice and similar results as reported were obtained.

For isolation of the products: 1 mmol olefin was added to a stirred solution of 1 mmol AB in 5 ml THF in a 20 ml glass vial. After the required time the mixture was filtered over a small column with celite (usually a pipette stopped with cotton or a small piece of tissue can be used for the NMR reactions) and then the solvent was removed in vacuo (polyborazylene was filtered and borazine evaporated), the residue was further extracted with a unpolar solvent like hexane and the solvent was removed again (AB insoluble in hexane). The remaining residue was the pure hydrogenated product to the limit of NMR.

S4 Typical kinetic $^{11}$B NMR spectra

For reaction of 1a with AB (5 : 1 molar ratio) in acetonitrile at room temperature with 2 minutes intervals.
S5 In situ spectra for determination of the intermediate

(Reactions of 1a with AB with 3:1 molar ratio at -40°C).

$^1$H NMR in CD$_3$CN @ 500 MHz:

$^{13}$C NMR in CD$_3$CN @ 500 MHz:

$^{13}$C NMR in CD$_3$CN @ 500 MHz: enlarged scale

DEPT @ 500 MHz:

$^{13}$C, $^{1}$H$_{3}$ up, $^{1}$H$_{2}$ down, C($^{13}$) zero
C, H-Correlation in THF-D₈ @ 500 MHz:

B, H-Correlation in THF-D₈ @ 500 MHz: ↓

Broad triplet: ↓↓↓
Long range C, H-Correlation in THF-D₈ @ 500 MHz:

2D-ROSEY in THF-D₈ @ 500 MHz:
S6 NMR data of all the hydrogenated products.

All the hydrogenated products are described in literature, and the obtained NMR data match literature values.

2-Cyclohexylmalononitrile (2a), \(^{7,8}\) colorless liquid, \(\delta_H\) (ppm; 300 MHz; THF-D\(_8\)) 1.15-1.44 (m, 5 H, -CH-), 1.69-2.06 (m, 6 H, -CH-), 4.25 (d, \(J = 5\) Hz, 1 H, -CH-); \(\delta_C\) (ppm; 300 MHz; THF-D\(_8\)) 26.34, 26.41, 29.57, 30.76, 40.06, 113.64 (2 C, -CN).

Methyl 2-cyano-2-cyclohexylacetate (2b), \(^9\) colorless liquid: \(\delta_H\) (ppm; 300 MHz; CD\(_3\)CN) 1.08-1.35 (m, 5 H, -CH-), 1.63-1.82 (m, 5 H, -CH-), 1.94-2.07 (m, 1 H, -CH-), 3.64 (d, \(J = 5\) Hz, 1 H, -CH-), 3.74 (s, 3 H, -Me); \(\delta_C\) (ppm; 75.4 MHz; CD\(_3\)CN) 26.27, 26.34, 26.51, 30.00, 31.62, 39.43, 45.11, 53.83, 117.10 (-CN), 167.60 (-C=O).

2-Cyclopentylmalononitrile (2c), \(^7\) yellow liquid, \(\delta_H\) (ppm; 300 MHz; THF-D\(_8\)) 1.44-1.56 (m, 2 H, -CH\(_2\)-), 1.61-1.82 (m, 4 H, -CH\(_2\)-), 1.95-2.05 (m, 2 H, -CH\(_2\)-), 2.44-2.60 (m, 1 H, -CH-), 4.34-4.36 (d, \(J = 7\) Hz, 1 H, -CH-); \(\delta_C\) (ppm; 75.4 MHz; THF-D\(_8\)) 26.06, 27.66, 31.05, 41.71, 114.20 (-CN).

2-Isopropylmalononitrile (2d), \(^7\) yellow liquid, \(\delta_H\) (ppm; 300 MHz; THF-D\(_8\)) 1.19 (d, \(J = 7\) Hz, 6 H, -Me), 2.28-2.41 (m, 1 H, -CH-), 4.26 (d, \(J = 6\) Hz, 1 H, -CH-); \(\delta_C\) (ppm; 75.4 MHz; THF-D\(_8\)) 19.58, 30.50, 31.74, 113.70 (-CN).

2-(3,3-Dimethylbutan-2-yl)malononitrile (2e), \(^8\) colorless liquid: \(\delta_H\) (ppm; 300 MHz; CD\(_3\)CN) 0.98 (s, 9 H, -Me), 0.99 (s, 3 H, -Me), 1.23-1.27 (m, 1 H, -CH-), 4.22-4.25 (m, 1 H, -CH-); \(^{13}\)C-NMR (CD\(_3\)CN): \(\delta\) (ppm) 13.00, 26.56, 27.47, 34.36, 45.54, 115.72 (-CN).
2-(1-Phenylpropyl)malononitrile (2f),\(^1\) white solid: \(\delta_H (\text{ppm}; 300 \text{ MHz}; \text{CD}_3\text{CN})\) 0.81 (t, \(J = 7 \text{ Hz}, 3 \text{ H}, \text{-Me})\), 1.89-1.99 (m, 2 H, \(-\text{CH}_2\)), 3.20-3.27 (m, 1 H, \(-\text{CH})\), 4.36 (d, \(J = 7 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 7.35-7.54 (m, 5 H, \(-\text{CH}=-\)); \(^{13}\text{C-NMR (CD}_3\text{CN)}\) \(\delta (\text{ppm})\) 11.85, 26.24, 30.63, 48.09, 114.04 (-\text{CN}), 129.13, 129.37, 129.86, 138.54.

2-Benzhydrylmalononitrile (2g),\(^2\) white solid, \(\delta_H (\text{ppm}; 300 \text{ MHz}; \text{THF-D}_8)\) 4.81 (d, \(J = 9 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 5.29 (d, \(J = 9 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 7.23-7.44 (m, 10 H, \(-\text{CH}=-\)); \(\delta_C (\text{ppm}; 75.4 \text{ MHz}; \text{THF-D}_8)\) 28.98, 52.14, 113.87 (-\text{CN}), 128.89, 129.60, 129.80, 139.70.

2-(9H-fluoren-9-yl)malononitrile (2h),\(^3\) white solid, \(\delta_H (\text{ppm}; 300 \text{ MHz}; \text{THF-D}_8)\) 4.59 (d, \(J = 3.5 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 5.18 (d, \(J = 4.5 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 7.34-7.51 (m, 4 H, \(-\text{CH}=-\)); \(\delta_C (\text{ppm}; 75.4 \text{ MHz}; \text{THF-D}_8)\) 27.78, 46.95, 113.41 (-\text{CN}), 121.41, 125.63, 128.67, 130.07, 142.00, 142.64.

2-benzylmalononitrile (2i),\(^4\) slightly yellow solid: \(\delta_H (\text{ppm}; 300 \text{ MHz}; \text{THF-D}_8)\) 3.31 (d, \(J = 7 \text{ Hz}, 2 \text{ H}, \text{-CH}_2\)), 4.59 (t, \(J = 7 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 7.32-7.38 (m, 5 H, \(-\text{CH}=-\)); \(\delta_C (\text{ppm}; 75.4 \text{ MHz}; \text{THF-D}_8)\) 25.25, 36.91, 114.19 (-\text{CN}), 128.90, 129.61, 130.19, 135.65.

Methyl 2-cyano-3-phenylpropanoate (2j),\(^5\) white solid: \(\delta_H (\text{ppm}; 300 \text{ MHz}; \text{CD}_3\text{CN})\) 3.10-3.32 (m, 2 H, \(-\text{CH}_2\)), 3.74 (s, 3 H, \(-\text{Me})\), 4.01-4.13 (m, 1 H, \(-\text{CH})\), 7.25-7.41 (m, 5 H, \(-\text{CH}=-\)); \(\delta_C (\text{ppm}; 75.4 \text{ MHz}; \text{CD}_3\text{CN})\) 35.47, 39.80, 53.53, 117.07 (-\text{CN}), 127.96, 129.11, 129.59, 136.55, 166.89 (-\text{C}=\text{O}).

Dimethyl 2-benzylmalonate (2k),\(^6\) colorless liquid: \(\delta_H (\text{ppm}; 300 \text{ MHz}; \text{CD}_3\text{CN})\) 3.13-3.17 (d, \(J = 8 \text{ Hz}, 2 \text{ H}, \text{-CH}_2\)), 3.63 (s, 6 H, \(-\text{Me})\), 3.71 (t, \(J = 8 \text{ Hz}, 1 \text{ H}, \text{-CH})\), 7.09-7.36 (m,
\[ \text{5 H, -CH=); } \delta_C \text{ (ppm; 75.4 MHz; CD}_3\text{CN)} \text{ 35.30, 53.04, 54.35, 127.70, 129.46, 129.76, 139.03, 170.12 (-C=O).} \]

References:


