Frustrated Lewis Pairs

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Coupling of Carbon Monoxide with Nitrogen Monoxide at a Frustrated Lewis Pair Template

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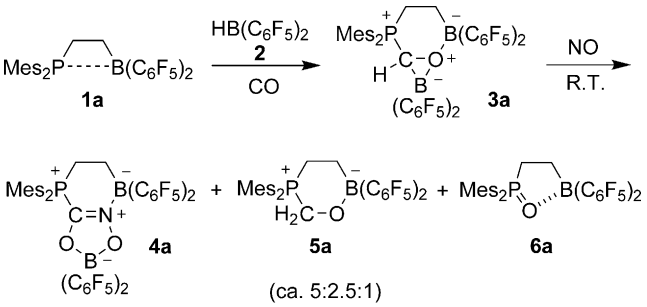
Dedicated to Professor Dieter Hoppe on the occasion of his 75th birthday

Abstract: *Coupling of carbon monoxide with nitrogen monoxide was achieved at a frustrated Lewis pair template. This unique reaction uses hydride as an auxiliary, which reductively activates carbon monoxide at the frustrated Lewis pair. The CO/NO coupling reaction then takes place through a pathway involving a radical reaction in which the hydrogen atom auxiliary is eventually removed again.*

The two-atom main-group-element oxides nitrogen monoxide (nitric oxide, NO) and carbon monoxide (CO) are both of enormous technical importance and, therefore, both of them are produced and used in vast quantities. Nitrogen monoxide is an intermediate in ammonia oxidation and CO has found many important uses, for example, in methanol synthesis and hydroformylation. Nitrogen monoxide is an essential physiological molecule. It has been shown to serve in a signaling role in the cardiovascular system and has been found to be involved in many more physiological functions.[1] Carbon monoxide has also been found in vivo and a complex function for this molecule in living systems has recently been unveiled as well.[2] Because of the vast technical as well as biochemical importance of these molecules, the chemistry of both NO and CO has been extensively studied and very significantly developed. However, reactions involving both CO and NO jointly in an active role are rare and, to the best of our knowledge, their direct coupling in a metal-free environment has not been developed.[3] We have now found a way to couple CO with NO at a frustrated Lewis pair (FLP) template.[4]

Carbon monoxide is not reduced by [B]H boranes,[5,6] but we have shown that CO is readily reduced to the formylborane stage by the [B]H borane $[HB(C_6F_5)_2]$ at a variety of saturated vicinal phosphane/borane frustrated Lewis pairs (P/B FLPs).[7] As a typical example of this class of compounds, the P/B FLP stabilized η^2-formylborane product **3a** has been obtained in good yield from the ethylene-bridged P/B FLP **1a**,[8,9] Piers' borane $[HB(C_6F_5)_2]$ (**2**),[10] and carbon monoxide.

We were also able to show that Piers' borane alone reacts with CO only to give the "Piers' borane carbonyl" $(C_6F_5)_2B(H)$-(CO).[11] We have now reacted the η^2-formylborane/FLP product with NO (Scheme 1).[12–15] Exposure of **3a** in D_6-benzene solution to a nitrogen monoxide atmosphere (1.5 bar) rapidly resulted in complete conversion (30 min at RT) of the starting material to give a mixture of two major compounds (**4a** and **5a**) and a minor byproduct (**6a**) in a ratio of ca. 5:2.5:1 (by ^1H/ ^{31}P NMR spectroscopy), plus some additional unidentified boron-containing components. The latter are probably $(C_6F_5)_2B$ oxides or hydroxides.



Scheme 1. CO/NO coupling at a frustrated Lewis pair template.

We specifically changed the reaction conditions in order to isolate the main reaction products in pure form and to gain information about their formation. We first treated the η^2-formylborane/FLP starting material **3a** with NO (1.5 bar, RT, 2 h, toluene) in the presence of 3 Å molecular sieves. Scavenging the in situ formed H_2O furnished compound **4a** from CO/NO coupling at the P/B FLP framework as the major product. Workup, including crystallization from dichloromethane/*n*-pentane, eventually gave analytically pure product **4a** in 55% yield as a white solid (Scheme 2).

We then treated the starting material **3a** in CD_2Cl_2 with water (30 min, RT). In situ NMR spectroscopy of the reaction mixture showed that the formaldehyde P/B FLP adduct product **5a** had been formed, along with some unidentified $(C_6F_5)_2BO$ products (Scheme 2). In a separate experiment, we reacted NO with 1,4-cyclohexadiene in D_2-dichloromethane solution. We expected that H-atom abstraction[16] by the rather unreactive NO radical[17] would reveal itself through the formation of benzene, and this was indeed observed. Over a period of 6 h, approximately 80% conversion of 1,4-cyclohexadiene into benzene occurred and was monitored

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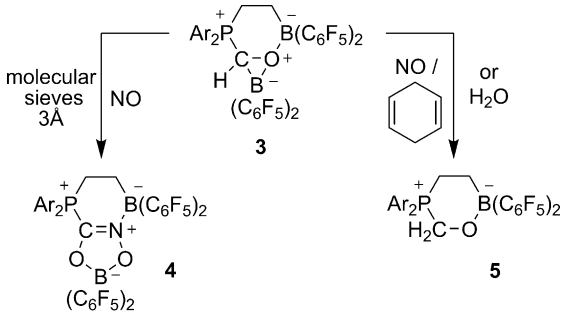


Scheme 2. Reactions of η^2-formylborane/FLP adducts with nitric oxide.

by in situ NMR spectroscopy.[18] We assume that this reaction generated nitroxyl (HNO),[19–22] which under our reaction conditions would rather rapidly decompose to N_2O and H_2O. Therefore, we carried out a second series of experiments where we exposed an approximately 1:10 mixture of the η^2-formylborane/FLP starting material **3a** and 1,4-cyclohexadiene to NO. Sure enough, the major reaction product was now the formaldehyde P/B FLP adduct **5a** (plus the unidentified B oxides). Workup of the reaction mixture, including crystallization from dichloromethane/*n*-pentane, eventually gave the pure product **5a** as a white solid in 53% yield (Scheme 2).

The products **4a** and **5a** were both characterized by C,H,(N) elemental analysis, NMR spectroscopy, and X-ray diffraction. Single crystals of the CO/NO coupling product **4a** were obtained from dichloromethane/*n*-pentane at −30 °C. X-ray crystal structure analysis revealed the formation of a heterobicyclic framework that contained a central C=N double bond between the CO-derived carbon atom C3 and the NO-derived nitrogen atom N1 (N1–C3 distance: 1.299(3) Å). Both the C3 ($\Sigma C3^{PON} = 359.6°$) and N1 ($\Sigma N1^{OCB} = 359.7°$) atoms show trigonal planar coordination geometries. The five-membered ring substructure is almost planar, while the anellated six-membered heterocyclic ring shows a distorted half-chair conformation (Figure 1).

Compound **4a** shows well resolved NMR spectra. The position of the CO-derived carbon atom C3 was spectroscopically determined from an experiment using ^{13}C isotopically labelled carbon monoxide. Compound **4a** shows a ^{31}P NMR resonance at $\delta = 13.3$ with a coupling constant of $^1J_{PC} = 106$ Hz, and a pair of ^{11}B NMR resonances ($\delta = 11.5$ and $\delta = -6.2$). Consequently, the ^{19}F NMR spectrum shows two sets of *o*,*p*,*m*-fluorine resonances for the pair of $B(C_6F_5)_2$ moieties (for details see the Supporting Information). The ^{13}C NMR signal of the C(3)=N carbon atom was located at $\delta = 154.0$.

The formaldehyde P/B FLP adduct **5a** was also characterized by X-ray diffraction. It shows a distorted boat-shaped conformation of the six-membered heterocyclic ring system (Figure 2). The compound shows NMR signals at $\delta = 16.0$ (^{31}P), $\delta = -1.0$ (^{11}B), and $\delta = 64.4$ ($^1J_{PC} = 42.3$, ^{13}C of OCH_2), in addition to the typical FLP framework NMR resonances (see the Supporting Information for details).

The formation of the CO/NO coupling product **4a** is not the only example of this reaction type. We found another

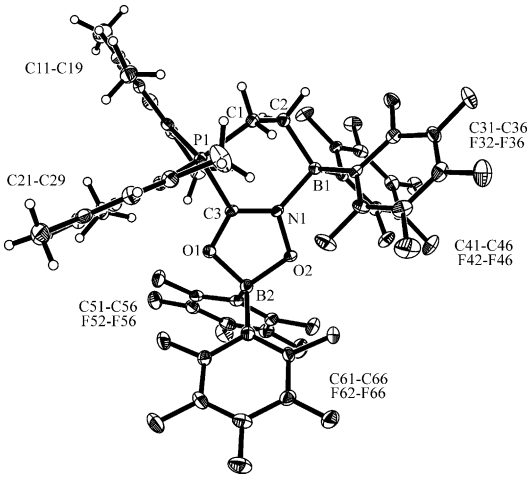


Figure 1. X-ray crystal structure analysis of the CO/NO coupling product **4a** (thermal ellipsoids are shown at 50%). Selected bond lengths (Å) and angles (°): C3–P1 1.823(2), C3–N1 1.299(3), N1–B1 1.596(4), C3–O1 1.310(3), N1–O2 1.392(3), B1-N1-C3-P1 −14.1(4), O2-N1-C3-O1, −0.3(3) $\Sigma C3^{PON} = 359.6$, $\Sigma N1^{OCB} = 359.7$.[35]

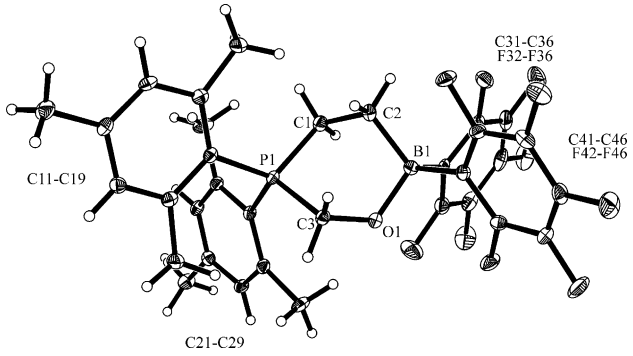


Figure 2. X-ray crystal structure analysis of the compound **5a** (thermal ellipsoids are shown at 50%). Selected bond lengths (Å) and angles (°): C3–P1 1.847(2), C3–O1 1.400(2), O1–B1 1.503(2), P1-C3-O1 109.0(1), C3-O1-B1 117.2(1).[35]

system that behaved analogously. The reaction of the new P/B FLP **1b**, prepared through $HB(C_6F_5)_2$ hydroboration of bis(2,6-dimethylphenyl)vinylborane, with CO and $HB(C_6F_5)_2$ under our reaction conditions gave the η^2-formylborane P/B FLP adduct **3b**, which was isolated as a white solid in 71% yield. The new compound features typical NMR parameters [^{31}P: $\delta = 32.8$, ^{11}B: $\delta = -5.9$ and $+6.0$, formyl moiety: $\delta = 5.54$ (^1H), $\delta = 54.7$ (^{13}C)]. Compound **3b** was characterized by X-ray diffraction (Figure 3).

The reaction of the η^2-formylborane P/B FLP adduct **3b** with nitrogen monoxide at near to ambient conditions gave the CO/NO coupling product **4b** in the presence of 3 Å molecular sieves. It was isolated as a white solid in 52% yield after crystallization. Compound **4b** was characterized by X-ray diffraction. It contained a C3–N1 C=N double bond of a similar length (1.304(3) Å) to that found for **4a** (see the Supporting Information for structural details and spectroscopic characterization of **4b**). In the presence of the 1,4-cyclohexadiene H-atom donor, the reaction of **3b** with NO

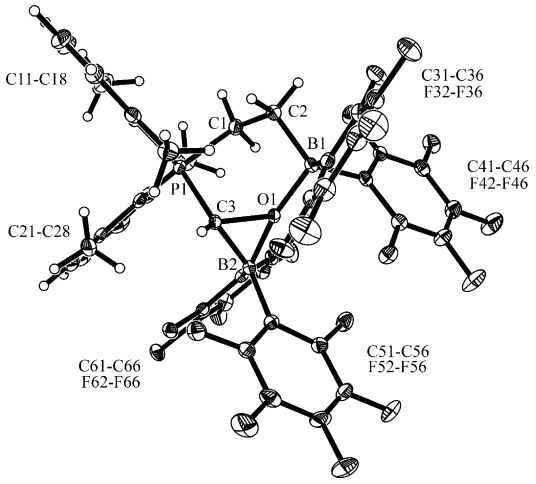
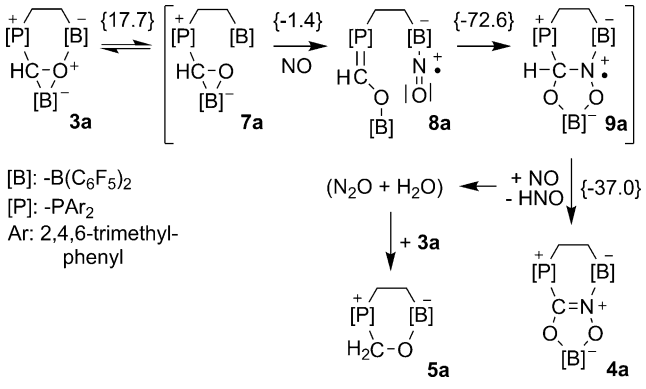


Figure 3. X-ray crystal structure analysis of the η^2-formylborane P/B FLP adduct **3b**. Thermal ellipsoids are shown at 50%. Selected bond lengths (Å) and angles (°): C3–P1 1.835(2), C3–O1 1.462(2), O1–B1 1.571(2), C3–B2 1.603(2), O1–B2 1.528(2), $\Sigma C3^{POB} = 292.2$, $\Sigma O1^{BCB} = 359.8$.[35]

took a different course: in this case the formaldehyde P/B FLP adduct **5b** was formed at the expense of the CO/NO coupling product **4b**. We isolated compound **5b** from the reaction mixture in 60% yield after crystallization (see the Supporting Information for characterization).

We assume that the CO/NO coupling sequence is initiated by reversible dissociation of the B–O bond in the six-membered ring of the starting material **3** (Scheme 3). This is supported by trapping of the resulting opened intermediate **7** by various donors.[23] We assume that NO can add to the intermediate **7** to form **8**. It is likely that the P-formylborane moiety in **8** has a reactivity that can be illustrated by an ylidic resonance form (or even an equilibrating ylidic isomer).[23a] Since the [B]-NO intermediate probably has electrophilic character at nitrogen (similar to HNO), subsequent C–N bond formation can occur by nucleophilic attack to generate the ring-closed N-centered radical **9**. Hydrogen atom abstraction by NO would then eventually form the observed CO/NO coupling product **4**. The resulting in situ formed nitroxyl HNO would then probably decompose to give N_2O and water, which would subsequently serve to hydrolyze one equivalent of the starting material **3** to yield **5** if it was not removed by other means, for example, by the addition of molecular sieves.



Scheme 3. Possible reaction scheme for the CO/NO coupling reaction with computed Gibbs energies {kcal mol^{-1}} at the PW6B95-D3/def2-TZVP(COSMO-RS, toluene)//TPSS-D3/def2-TZVP level of theory. The values refer to reaction free energies for the step denoted by the arrow (see the Supporting Information for details).

This mechanistic scheme is supported by the results of DFT calculations. All of the structures were optimized at the dispersion-corrected TPSS-D3 level of theory,[24–26] with a Gaussian AO basis set of def2-TZVP quality,[27,28] followed by single-point energy calculations at the PW6B95-D3 level[25,26,29] with the same basis set. The conductor-like screening model for real solvents (COSMO-RS) solvation model[30,31] was used to compute the solvation Gibbs free energies for toluene as the solvent (for details, see the Supporting Information). It revealed that the initial B–O dissociation step (i.e., opening of the six-membered ring) leading to **7** is endergonic and the subsequent NO addition is almost thermoneutral (Scheme 3), but ring closure to give the heterocyclic radical intermediate **9** is strongly exergonic (−72.6 kcal mol^{-1} in the case of two mesitylene groups on the phosphorus atom). For the validity of this reaction mechanism, it is significant that the next step, the H-atom abstraction by NO to eventually give the diamagnetic CO/NO coupling product **4** and nitroxyl (HNO), is again strongly exergonic, with a calculated reaction energy of −37 kcal mol^{-1} with -$PMes_2$. In short, the formation of product **4**, which contains coupled CO and NO molecules, is strongly favored by the ring closure, in which a central C=N double bond and a B–O bond are formed, and the H-atom abstraction, which is accomplished by a NO molecule.

Formally, our overall reaction could be regarded as involving disproportionation of two NO equivalents to NO^+ and (singlet or triplet) NO^-,[32] with the former being used to form the CO/NO coupling product **4** by reaction with the **3/7** system followed by loss of a proton, and the later generating HNO by protonolysis, although in reality our reaction very likely follows a completely different mechanistic pathway involving typical radical chemistry. However, our study shows that NO/HNO chemistry, which is so important physiologically,[33,34] can be performed in a completely artificial environment and can serve to couple the essential two-atom-containing main-group-element oxides carbon monoxide and nitrogen monoxide .

Experimental Section

Preparation of compound **4a**: A mixture of compound **3a** (320.0 mg, 0.315 mmol), molecular sieves (3 Å, 630 mg), and toluene (20 mL) was degassed by freeze-pump-thaw cycles (×2). Then the cooled (0 °C) reaction mixture was carefully evacuated and exposed to NO gas (1.5 bar). After the reaction mixture was stirred at room temperature for 2 hours, it was filtered and the separated molecular sieves were washed with CH_2Cl_2 (2×5 mL). The solvent of the filtrate was then removed under reduced pressure, the resulting residue was washed with *n*-pentane (2×10 mL) and dried under reduced pressure. The obtained solid material was crystallized from CH_2Cl_2 (1 mL) and *n*-pentane (5 mL) to give compound **4a** as white powder (180.1 mg, 0.172 mmol, 55%).

Preparation of compound **5a**: A solution of compound **3a** (134.5 mg, 0.132 mmol) and 1,4-cyclohexadiene (105.6 mg,

1.32 mmol) in toluene (10 mL) was degassed by freeze-pump-thaw cycles (×2). Then the cooled (0 °C) reaction mixture was carefully evacuated and exposed to NO gas (1.5 bar). After the reaction mixture was stirred at room temperature overnight, the solvent was removed under reduced pressure, and the resulting residue was washed with *n*-pentane (10 mL) and dried under reduced pressure. The obtained solid material was crystallized from CH_2Cl_2 (0.3 mL) and *n*-pentane (1.5 mL) to give compound **5a** as a white powder (46.8 mg, 0.070 mmol, 53 %).

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Keywords: boron · carbon monoxide · frustrated Lewis pairs · nitric oxide · phosphorus

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