Redox-active formazanate ligands are emerging as tunable electron-reservoirs in coordination chemistry. Here we show that boron diphenyl complexes with formazanate ligands, despite their (formal) negative charge, can be further reduced by up to two electrons. A combined crystallographic, spectroscopic and computational study establishes that formazanate ligands are stable in mono-, di- and trianionic form.

Coordination complexes containing ligand systems that are accessible in several oxidation states (‘redox-active’ ligands) are attractive for catalysis\(^1\) as well as materials applications.\(^2\) Several classes of redox-active ligands are known but those that combine a modular, straightforward synthesis with excellent chemical stability across two (or more) different redox-states remain scarce. Lappert and co-workers have reported ligand-based reduction chemistry of the popular class of β-diketiminates,\(^3\) but these compounds are accessible only at very negative potentials (using strong reducing agents). Taking inspiration from the work by Hicks and co-workers,\(^4\) our group has started to investigate the (redox-)chemistry of formazanate ligands in coordination compounds. In recent years, we\(^5\) as well as others\(^6,7,8\) have taken advantage of the unusual chemistry and photophysics that formazanate ligands provide. In attempts to characterize in more detail the structures that result from ligand-based redox reactions in formazanate compounds, we reported previously that cyclic voltammograms of boron difluoride complexes indicate two sequential reductions take place to form the redox-series [LBF\(_2\)]\(^{0/-1/-2}\).\(^9\) Attempts to isolate the most reduced member of this series, the dianion [LBF\(_2\)]\(^-2\), resulted in elimination of boron difluoride (1.5589(16)/1.5520(16) Å) in the corresponding boron difluoride (1.5990(15)/1.5955(15) Å) in the difluoride analogue, with the B atom displaced out of the plane defined by the 4 N atoms by 0.685 Å giving rise to crystallographically distinct B-Ph groups.\(^9\) Here we report (formazanate)boron diphenyl complexes that lead to stable 2-electron reduction products which are characterized by spectroscopic and crystallographic methods.

Stable, crystalline boron complexes with mono-, di- and trianionic formazanate ligands

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The electrochemical properties of compound 2a were established by cyclic voltammetry in THF solution (Figure 1), which shows two quasi-reversible 1-electron redox-events at -1.35 and -2.26 V vs. Fc\(^{0/+}\). In comparison with the boron difluoride analogues, the reduction potentials for 2a are shifted to more negative potentials due to the presence of less electron-withdrawing B-substituents (Ph vs F). As anticipated, replacing an N-Ph substituent for N-Mes on the formazanate backbone (2b) results in a shift of the redox-potentials to more negative values. Moreover, the second reduction is clearly less reversible for 2b and a new oxidation wave is observed at \(E_{\text{a,b}} = -1.26\) V that likely results from a chemical transformation of the initial 2-electron reduction product.

Chemical synthesis and subsequent characterization of the reduction products of 2 was attempted. The radical anions 3a/b were generated via treatment with 1 equiv of Cp*₂Co and could be isolated as green crystalline material in good yield (structure of 3b shown in Fig. 2). More surprisingly, the reaction of compounds 2 with 2 equiv of Na/C₆H₆ as reducing agent resulted in the clean formation of the dianions [(formazanate)BPh₂]²⁻, which were obtained in moderate yield as orange crystals of their disodium salts (4b) upon precipitation from THF/hexane (Scheme 1). While the 2-electron reduction of formazanate boron fluoride results in facile cleavage of both B-F bonds to form 2 equiv of NaF and a (transient) boron carbeneoid species, the B-Ph bond in 4a/b is thermally stable: when kept in THF solution at room temperature under an inert atmosphere no decomposition is noticeable over several days.

Single-crystal X-ray diffraction studies for compounds 3 and 4 show distorted tetrahedral geometries around the boron centre, with the ligands bound via the terminal N atoms to give 6-membered chelate rings (Figure 2). In comparison to the neutral precursor 2a, compounds 3 and 4 show progressive elongation of the N-N bonds (e.g., 2a: 1.3060(13)/1.3090(13) Å; 3a: 1.369(4)/1.373(4) Å; 4a: 1.428(3)/1.433(3) Å), consistent with ligand-based reduction which populates the ligand N-N π*-orbitals. At the same time, the N-C(Ar) distances shorten upon reduction, which is consistent with delocalization of electron-density into the N-Ar rings (vide infra). The crystal structure of compound 4a (figure 2, middle) shows that in the solid state, the two Na⁺ ions are coordinated to the dianionic boron complex via the internal N atoms of the formazanate ligand (closest contacts are Na-N distances of 2.351(2) and 2.390(2) Å). In contrast to 4a, the solid state structure of 4b (figure 2, right) reveals a dimeric structure: the asymmetric unit contains two [(formazanate)BPh₂]²⁻ moieties that are bridged by two Na⁺ cations. Both of these sit in a coordination pocket formed by formazanate N-atoms and aromatic groups, so that no (for Na(1)) or only one additional THF molecule (for Na(2)) is bound to the cation. Interaction of alkali metal cations with the C(π) atoms of aromatic rings is increasingly recognized as an important structural element. Several relatively close contacts (<2.9 Å) between Na⁺ cations and aromatic carbon atoms are observed, but this does not lead to significant distortions within the aromatic rings. Thus, individual Na⁺-C(π) interactions are likely weak, but collectively they are sufficiently stabilizing to successfully compete with the more common O-donors of the THF solvent. The Mes-substituted N(4) and N(5) atoms in 4b are significantly pyramidalized (Σ∠(N) = 346.1 and 345.0°), but those substituted with a Ph group are not (av. 357.5°). This distortion is likely due to steric hindrance forcing the Mes group to rotate out of the plane of the ligand backbone, which prevents delocalization of π-electron density from the electron-rich formazanate backbone into the Mes ring. This is also borne out by the large difference between the N-C(Ph) and N-C(Mes) bond lengths (1.379(4)/1.377(3) and 1.435(4)/1.429(4) Å, respectively) that is in agreement with substantial double bond character for the N-C(Ph) groups.
In comparison to the neutral compounds 2, the $^{11}$B NMR resonances in (diamagnetic) dianions 4 are shifted upfield by ca. 3 ppm, in agreement with more electron-rich compounds. The NMR resonances for the $p$-CH of the N-Ph groups in diation $4a$ are found at $\delta$ 5.85 (1H) and 109.7 ppm (13C) due to significant charge-delocalization into the aromatic N-substituents of the formazanate ligand. For compound $4b$, the $^1$H NMR spectrum at room temperature (400 MHz, THF-$d_8$ solution) shows exchange broadening of the N-Ph group while the other resonances are sharp. Upon decreasing the temperature, decoalescence occurs at ca. 15 °C to reveal 5 inequivalent $^1$H environments for the N-Ph group due to restricted rotation around the N-C(Ph) bond. In contrast to $4b$, the N-Ph resonances in $4a$ do not show this behaviour and exchange-averaged (albeit somewhat broadened) $^1$H NMR resonances are observed down to -60 °C. We attribute this difference to the fact that in $4a$, resonance delocalization from the electron-rich, reduced formazanate backbone occurs into two aromatic groups (N-Ph), whereas in $4b$ the perpendicular orientation of the N-Mes group does not allow this and only one N-Ph is involved. As a consequence, in $4b$ there is more substantial N=C(Ph) double bond character which results in the restricted rotation observed experimentally. NMR lineshape analysis$^{12}$ for compound $4b$ in the temperature range between -30 and + 65 °C allowed determination of the activation parameters for the exchange process as $\Delta H^\ddagger = 57.4 \pm 1.8$ kJ·mol$^{-1}$ and $\Delta S^\ddagger = 1 \pm 6$ J·mol$^{-1}$·K$^{-1}$ (see SI for details). Thus, the barrier to rotation is much higher than measured for the N-Ar bond in anilines ($\Delta G^\ddagger = 25.5$ kJ·mol$^{-1}$ for N-methylaniline)$^{13}$.

Although it is not as high as that in amides (70 – 95 kJ·mol$^{-1}$)$^{14}$, it indicates significant N-C(Ph) $\pi$-bonding due to the highly reduced nature of the formazanate ligand in 4.

The solution EPR spectra of compounds 3 are more complex than the nine-line signals usually observed for organic verdazyl radicals,$^{15}$ and show a multitude of hyperfine interactions. Simulation of the spectrum gave a satisfactory fit with inclusion of two pairs of (inequivalent) N atoms as well as the ortho/para phenyl-H and B atoms (Fig. 3 and S2).

$\Delta$H$^\ddagger = 57.4 \pm 1.8$ kJ·mol$^{-1}$ and $\Delta S^\ddagger = 1 \pm 6$ J·mol$^{-1}$·K$^{-1}$ (see SI for details).

Gas phase DFT (B3LYP/6-311+G(d,p)) calculations were performed on the [{formazanate}BPh$_3$]$^{0/-1/-2}$ compounds in the absence of the cations. The optimized geometries are in good agreement with the structures determined by crystallography.

In summary, we have shown that in boron diphenyl compounds, the monoanionic formazanate ligand can be cleanly converted to the corresponding dianionic (radical) and trianionic forms. The highly electron-rich ligand backbone in the latter complexes is stabilized by $\pi$-conjugation with the N-Ar substituents, leading to partial double bond character and restricted rotation of the N-C(Ph) bond.

We are currently exploring the (ligand-based) reactivity of these highly reduced main group complexes toward small-molecule activation.
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Notes and references

† CCDC 1508653-1508657 contain the crystallographic information for compounds 2a, 3a, 3b, 4a, and {4b}, in CIF format.

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