

Radical Chemistry

On the Synthesis, Characterization and Reactivity of N-Heteroaryl-Boryl Radicals, a New Radical Class Based on Five-Membered Ring Ligands

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Abstract: The synthesis and physical characterization of a new class of N-heterocycle-boryl radicals is presented, based on five membered ring ligands with a N(sp²) complexation site. These pyrazole-boranes and pyrazoboles exhibit a low bond dissociation energy (BDE; B–H) and accordingly excellent hydrogen transfer properties. Most importantly, a high modulation of the BDE(B–H) by the fine tuning of the N-heterocyclic ligand was obtained in this series and could be correlated with the spin density on the

boron atom of the corresponding radical. The reactivity of the latter for small molecule chemistry has been studied through the determination of several reaction rate constants corresponding to addition to alkenes and alkynes, addition to O₂, oxidation by iodonium salts and halogen abstraction from alkyl halides. Two selected applications of N-heterocycle-boryl radicals are also proposed herein, for radical polymerization and for radical dehalogenation reactions.

Introduction

Boryl radicals are versatile nucleophilic species that have recently triggered intense studies in organic synthesis.^[1] These radicals are classically produced through a hydrogen abstraction reaction between a borane and a suitable hydrogen acceptor. Historically,^[2] Roberts demonstrated in a series of elegant reports that boryl radicals derived from amine- or phos-

phine-boranes could be used in organic synthesis although their high bond dissociation energy (BDE; B–H) was a serious concern for applications in radical chain reactions. It should also be noted that their behavior as polarity reversal catalysts has been evidenced, thus clearly expanding their synthetic interest.^[3] Interestingly, it was demonstrated through theoretical approaches that the BDE(B–H) can be tuned by an appropriate design of the Ligand (L)^[4a,b] and that synergistic effects between the ligand and the substituents on the boron atom had a pronounced effect on the electronic structure of the boryl and also on its reactivity.^[4c]

A recent breakthrough has led to the development of a new class of boryl radicals based on N-heterocyclic carbene-boranes (NHC-boranes) that can efficiently overcome this BDE(B–H) limitation, the BDE(B–H) being brought down to about 80–90 kcal mol⁻¹ compared to 92–105 kcal mol⁻¹ for amine- or phosphine-boranes.^[1] NHC-boranes are now used in elegant chemical reactions such as radical reductions of xanthates and related derivatives where they serve as radical hydrogen atom donors in Barton-McCombie reactions.^[1] Based on quantum mechanical calculations, the 80–90 kcal mol⁻¹ range of BDE values can also be covered with some borane complexes containing five or six membered ring heterocycles with a N(sp²) complexation site for the borane moiety.^[5] Recently, N-heteroaryl-boranes such as **1a** (Figure 1), characterized by such a BDE(B–H) feature, have been reported by our laboratories and the formation as well as the reactivity of the associated boryl radicals were investigated.^[6,7] The kinetic data on boryl radicals remain, however, rather scarce.^[8]

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Supporting information for this article is available on the WWW under
<http://dx.doi.org/10.1002/chem.201400197>.

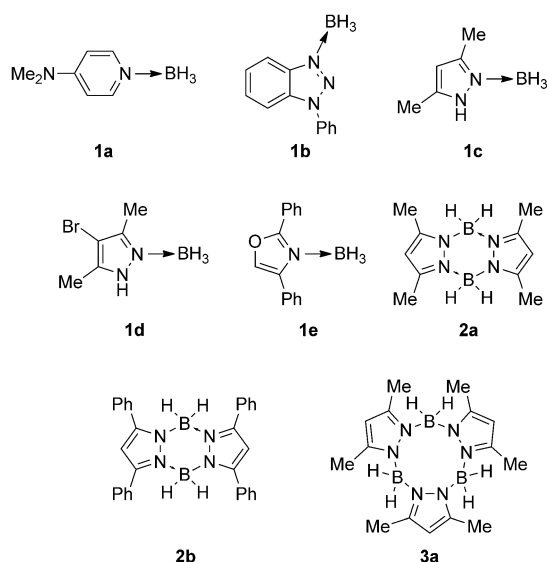


Figure 1. N-heteroaryl-borane complexes **1a-e**, pyrazaboles **2a, b** and polyborazane **3a**.

In the present paper, we report the synthesis, chemical mechanisms studies, and synthetic applications of **1b-e**, **2a, b**, and **3a** (Figure 1) that are the precursors of new boryl radical species based on five membered ring heterocycles such as pyrazoles, oxazoles, or triazoles. A clear modulation of the BDE(B-H) was expected and was accordingly demonstrated through DFT calculations. Kinetic data for the formation of these boryl radicals and for their interaction with alkenes, alkynes, O₂, iodonium salts, and alkyl halides are also provided for the first time. Structure/reactivity relationships of these new radicals, both in hydrogen abstraction process and in small molecule radical chemistry, are also discussed. Finally, two selected applications of these N-heterocycle-boranes are presented in thermal and photoinduced radical polymerization and also in radical dehalogenation reactions.

Results and Discussion

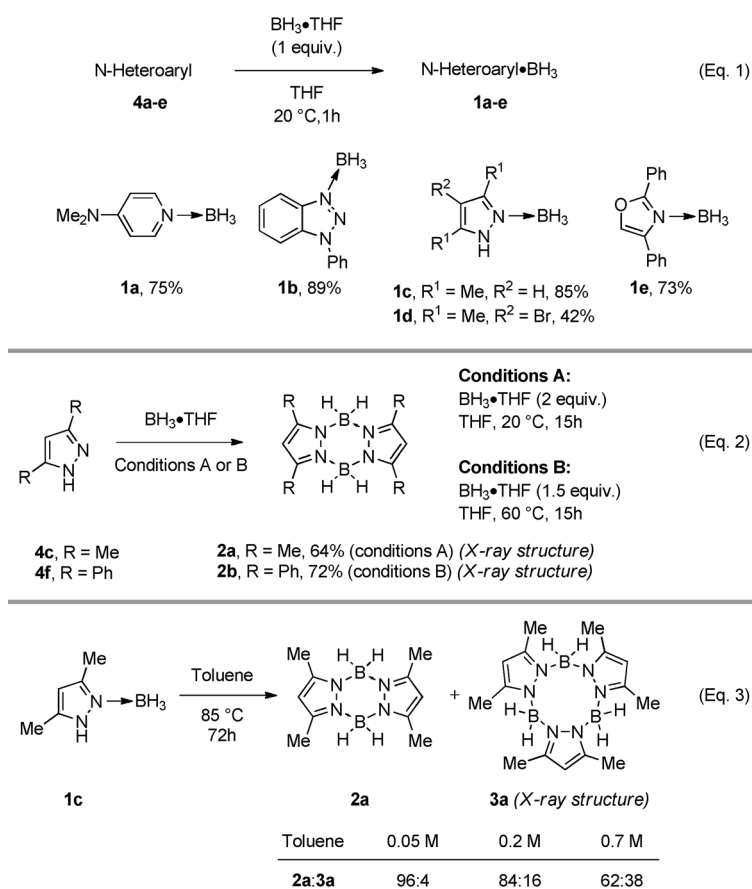
Synthesis of N-heterocycle borane complexes

N-heteroaryl borane complexes **1a**,^[6,7] **b**,^[14] **c**,^[15] **d**, and **e** were easily synthesized from the corresponding N-heteroarenes **4a-e** and borane-THF complex in THF at room temperature (Scheme 1, Eq. 1). These white and non-hygroscopic powders proved to be shelf stable and could be kept for months open to air. Interestingly, it was found that pyrazabole **2a** could be obtained in good yield (64%) on a large scale (50 mmol) when the reaction was run with an excess of borane-THF complex in THF at room temperature for 15 h (Scheme 1, Eq. 2, conditions A). On the other hand, access to pyrazabole **2b** required heating at reflux for an efficient dehydrogenative di-

merization (Scheme 1, Eq. 2, conditions B), in line with previous reports.^[16] The structures of these four-coordinate boron species were confirmed by X-ray diffraction studies (CCDC 981830 for **2a**; 981831 for **2b**, B-H 1.10–1.15 Å). As shown in Figure 2, pyrazabole **2a** possesses a classical B₂N₄ boat conformation of C_{2v} symmetry.^[17] Finally, heating a toluene solution of **1c** at 85 °C for 72 h delivered **2a** as the major product and also the nine-membered ring polyborazane **3a** as a minor component of the reaction, in a concentration-dependent fashion (Scheme 1, Eq. 3). At 0.05 M in toluene, only 4% of **3a** was obtained whereas at 0.2 M, 16% was found and at 0.7 M, up to 38% could be isolated. The structure of **3a** was determined by X-ray diffraction studies (CCDC 981833; B-H 1.10–1.12 Å, Figure 2).

Formation and reactivity of the N-heterocycle-boryl radicals

The boryl radicals are generated here in laser flash photolysis experiments through an approach based on a hydrogen abstraction reaction between the selected boranes and either 1) the *tert*-butoxyl radical *t*Bu-O• (reactions r1 and 2), the *t*Bu-O• radicals being easily generated at 355 nm by the direct cleavage of di-*tert*-butylperoxide^[9b] or 2) the benzophenone triplet state ³BP (reactions r3 and 4). In the case 1), the *tert*-butoxyl radical does not absorb at λ > 300 nm (Figure 3), the observed intense absorption can be ascribed to the generated boryl (see



Scheme 1. Synthesis of N-heteroaryl-borane complexes **1a-e**, pyrazaboles **2a, b** and polyborazane **3a**.

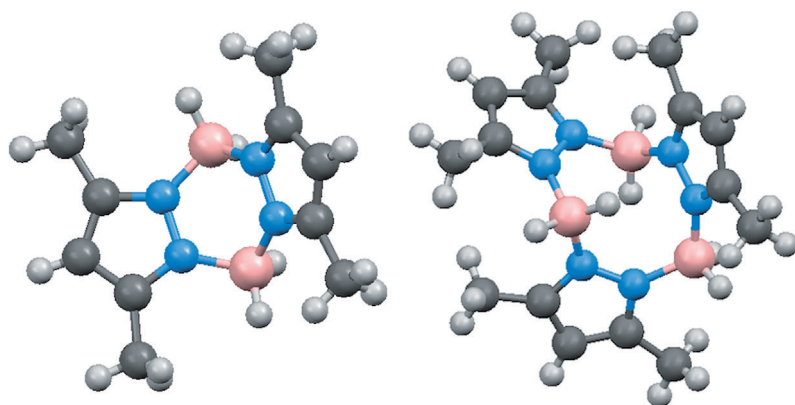


Figure 2. X-ray structures of pyrazabole **2a** (left; CCDC 981830) and polyborazane **3a** (right; CCDC 981833).

Figure 4 and the Supporting Information). The boryl radicals associated with **1** and **2** will be referred here as **1'** and **2'** for the sake of clarity.

The boryl absorption spectra spread over the visible range with absorption maxima at 430, 650, 640, 400, and 600 nm for **1b'-e'** and **2b'**, respectively. For **1b'** and **2b'**, the transient absorptions are relatively weak and the maximum absorption wavelength is not very well defined. The rise time of the boryl

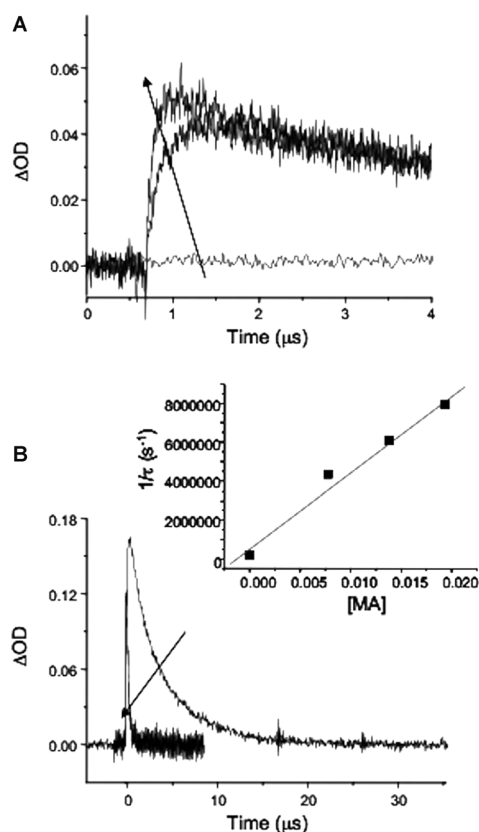


Figure 3. A) Kinetic traces recorded at 650 nm for the formation and decay of the boryl radical (**1c'**); the increase of [**1c'**] is indicated by an arrow. B) Kinetic traces recorded at 650 nm for the interaction of the boryl radical with methylacrylate (MA) in acetonitrile/*di-tert*-butylperoxyde; the increase of [MA] is indicated by an arrow. Insert: the associated Stern-Volmer treatment. Experiments performed under an argon atmosphere.

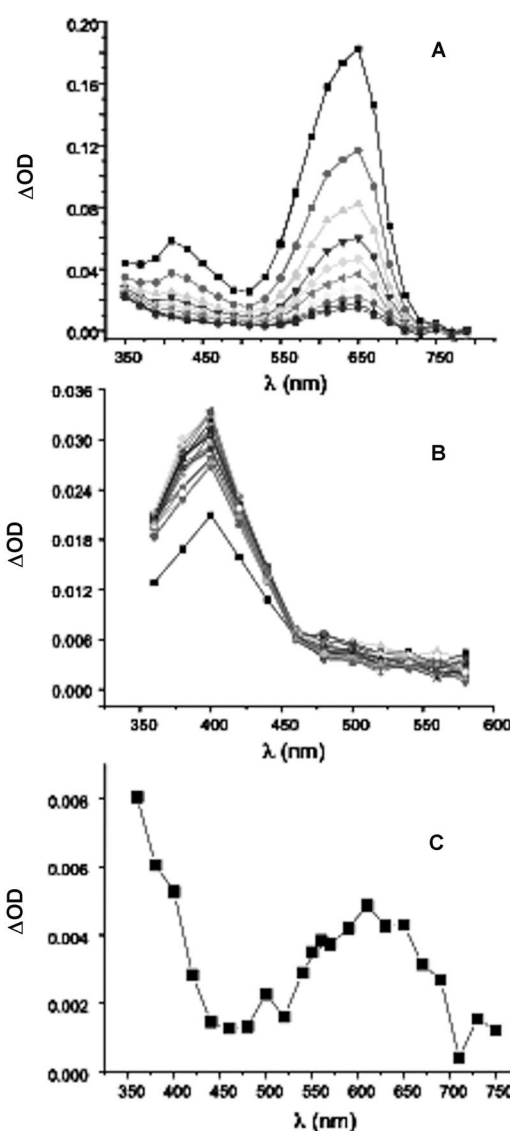


Figure 4. Transient absorption spectra of the radicals A) **1c'**, B) **1e'**, and C) **2b'** in acetonitrile/*di-tert*-butylperoxyde. The rise of the boryl radical occurs within 500 ns. Absorption recorded at different times after the laser excitation from 0.5 μ s to 19.8 μ s by steps of 1.94 μ s (A), 0.5 μ s to 8 μ s by steps of 420 ns (B); absorption recorded at $t = 1.5 \mu$ s (C).

absorption gives a direct access to the $t\text{Bu-O}^{\cdot}/\text{L} \rightarrow \text{BH}_3$ hydrogen abstraction rate constant (k_H); the k_H of the ${}^3\text{BP}/\text{L} \rightarrow \text{BH}_3$ interactions are also accessible through a quenching experiment (Table 1). Interestingly, high rate constants are found ($>10^8 \text{ M}^{-1} \text{ s}^{-1}$) in line with the quite low calculated BDE(B-H) values for the corresponding boranes (Table 1). The rate constants found for the $t\text{BuO}^{\cdot}/\text{borane}$ and ${}^3\text{BP}/\text{borane}$ reactions are quite similar. This suggests

Table 1. Rate constants (k_{H}) for the formation of the N-heterocycleborane radicals in acetonitrile/di-*tert*-butylperoxide at 20 °C; oxidation potential E_{ox} and calculated bond dissociation energy (BDE) of the boranes.

	E_{ox} [a]	BDE (B–H) [b]	k_{H} [c]	k_{H} [d]
1b	> 1	70.8	15	
1c	0.5	85.8	35	86 (1.0) [e]
1d		84.8	20	
1e	> 1	79.7	20 [b]	
2b	> 1	87.5	20 [b]	25 (0.8) [f]

[a] In V (vs. SCE); [b] in kcal mol⁻¹; [c] (tBu-O·, see r2), 10⁷ M⁻¹ s⁻¹; [d] (³BP, see r4), 10⁷ M⁻¹ s⁻¹; [e] the ketyl radical quantum yield (in acetonitrile) measured according to the classical procedure from ref. [9a]; it also corresponds to the boryl radical quantum yield; [f] a higher error bar is associated with these data due to noisy transients.

that the benzophenone triplet state generated after light absorption behaves like an alkoxyl radical leading to ketyl and boryl radicals. In this series of compounds, the selected N-heterocycle substituent can affect the BDE(B–H) by about 17 kcal mol⁻¹ that is, 70.8 kcal for **1b** versus 87.5 kcal mol⁻¹ for **2b**. This is in full agreement with a recent theoretical work which has shown that the complexation of the borane with a large number of small heterocycles can lead to BDE(B–H) in the 80–90 kcal mol⁻¹ range.^[5]

ESR-spin trapping (ESR–ST) is a worthwhile approach to characterize the free radicals generated.^[18,19] Typical results for ESR–ST are displayed in Figure 5. For the phenyl-*N-tert*-butylnitron (PBN9 adduct of **1c**), a third hyperfine splitting constant (HFS) a_{B} due to the boron nuclei must be included to reproduce the experimental spectra. The a_{B} value (4.1 G) is in excellent agreement with previous results on other boryls: $3.5 < a_{\text{B}} < 4.7$ G.^[2d,f] In the case of **1c**, the hydrogen abstraction reac-

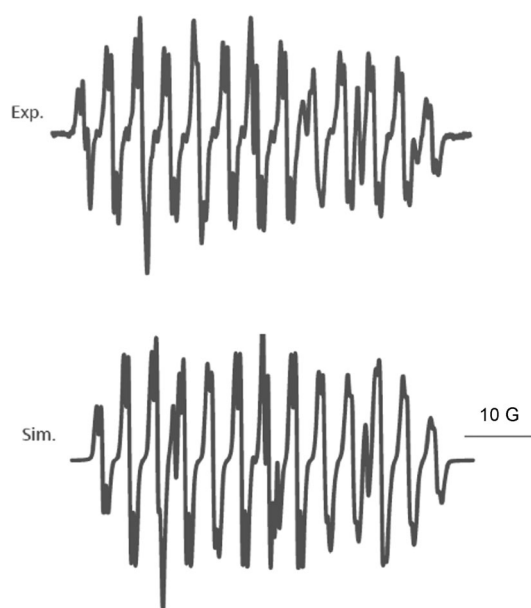
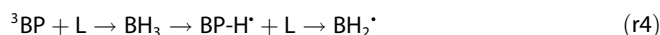


Figure 5. ESR spectrum observed in spin trapping experiments for the adduct of the boryl radical **1c** (using PBN) in *tert*-butylbenzene/di-*tert*-butylperoxide (fitting parameters $a_{\text{N}} = 16.3$ G; $a_{\text{H}} = 3.95$ G; $a_{\text{B}} = 4.1$ G; $a_{\text{H}} = 0.6$ G).

tion from the N–H bond can be ruled out as 1) the calculated BDE(N–H) is higher than BDE(B–H) by about 16 kcal mol⁻¹ and 2) no nitrogen centered radical is detected.



Through the direct observation of the boryl radicals in laser flash photolysis experiments, a convenient access to their reactivity became possible. Indeed, the classical analysis of the time dependence of the boryl decay provided the rate constants for their onward reactions with unsaturated compounds (alkenes or alkynes), oxygen, an oxidizing agent (diphenyliodonium hexafluorophosphate) and an alkyl halide (Figure 3, Table 2). Since the kinetics associated with the boryl radicals are strongly affected by O₂ (indeed, the boryl radical/O₂ interaction rate constants are close to the diffusion limit that is, for **1c**, $k = 2.3 \times 10^9$ M⁻¹ s⁻¹), the different quenching experiments with other molecules were all carried out under argon.

The boryl/alkene interaction rate constants correspond to an addition of the boryl to the alkene double bond (k_{add}), even in the case of acrylates. Indeed, the low interaction rate constant ($< 5 \times 10^5$ M⁻¹ s⁻¹) between for example, **1c** and a carbonyl group (acetone) compared to that of **1c** to methylacrylate (MA) evidences that the addition reactions to MA does not occur onto the carbonyl. The k_{add} s for the addition of the boryls to MA decrease in the series **1c** ~ **1d** > **2b** > **1b**, **1e** and span over at least two orders of magnitude, thereby highlighting the effect of the ligand on the boryl reactivity. The k_{add} of **1c** and **d** to MA is higher than that found for the triethylamine boryl derived radical **6** (Et₃N–BH₂·; $k_{\text{add}} = 1.3 \times 10^8$ M⁻¹ s⁻¹),^[8a] this latter species being characterized by the highest reported rate constant together with the 4-pyrrolidinopyridine borane derived radical **7** (4-pyrrolidinopyridine–BH₂·; $k_{\text{add}} = 1.4 \times 10^8$ M⁻¹ s⁻¹).^[6] Interestingly, **1c** exhibits also a high reactivity towards an alkyne (3.2×10^7 M⁻¹ s⁻¹ vs. 3.1×10^6 M⁻¹ s⁻¹ when considering **7**). These results support a very high reactivity of the new proposed boryl radicals.

The k_{add} values for the addition of a given boryl both to an electron rich alkene (ethylvinylether; EVE) and a less electron rich alkene (vinylacetate; VA) are almost similar and below 0.5×10^5 (**1c**, **d**) or 5×10^5 M⁻¹ s⁻¹ (**1e**, **2b**). As found in previous works on other N-heteroarylboryls or NHC-boryls,^[6,7,8b] the fast addition to an electron poor alkene (MA) combined with a slow addition to an electron rich alkene (VA and EVE) suggests that the boryls investigated here exhibit a high nucleophilic character. The transition state (TS) calculated for the addition of **1c** to MA is depicted in the Supporting Information. The barrier for the addition process is low (2.8 kJ mol⁻¹ at UB3LYP/6-31 + G* level) in full agreement with the measured high rate constants. Interestingly, a high charge transfer from the radical to the alkene is found in the transition state (TS;

	1 c[•] $k^{[a]}$	1 b[•] $k^{[a]}$	1 e[•] $k^{[a]}$	1 d[•] $k^{[a]}$	2 b[•] $k^{[a]}$
methylacrylate (MA)	39	< 0.03	< 1	40	2.5
methylmethacrylate (MMA)	26				
vinylacetate (VA)	< 0.05		< 0.5	< 0.05	< 0.5
ethylvinylether (EVE)	< 0.05		< 0.5	< 0.05	< 0.5
4-phenyl-1-butyne	3.2				
Ph ₂ I ⁺	250	120		250	0.8
C ₃ H ₇ I	40	< 0.05	< 0.1	49	
1-C ₆ H ₁₃ Br	0.25				

[a] 10⁷ M⁻¹ s⁻¹.

0.198 e) which is fully consistent with the high nucleophilic character of **1 c[•]**. This stems a general property that is, boryl radicals derived from amine-boranes, NHC-boranes and N-heteroaryl boranes being already characterized by a nucleophilic behavior.

1 c[•] being characterized by an enhanced reactivity compared to other boryls previously proposed, its oxidation by iodonium salt (Ph₂I⁺PF₆⁻) as well as its halogen abstraction property (from R-I or R-Br) were examined in detail. These elementary reactions are important in small molecule radical chemistry. Since they exhibit low reduction potentials (ca. -0.2 V), iodonium salts are often used to oxidize radicals.^[20] Interestingly, the rate constant close to the diffusion limit ($k > 10^9 \text{ M}^{-1} \text{ s}^{-1}$; Table 2) supports a very favorable oxidation process. This is in full agreement with the very low calculated ionization potential of **1 c[•]** (5.08 eV) as well as its nucleophilic character found above for the addition process. The rate constants (k_i) for the **1 c[•]** (and **1 d[•]**)/C₃H₇I interaction are very high (Table 2). As in the case of the addition to MA (see above), the reactivity of these

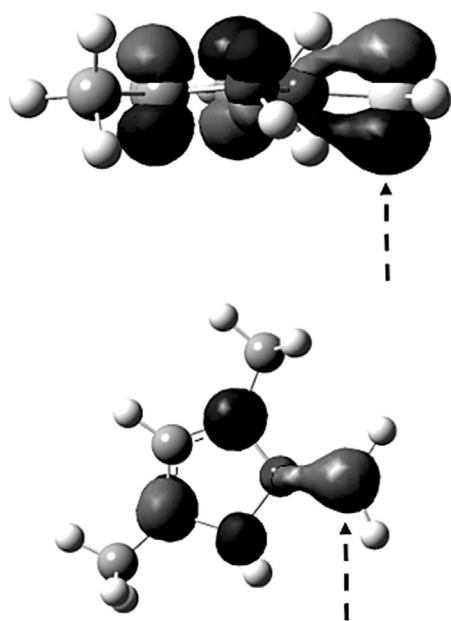


Figure 6. Singly occupied molecular orbital (SOMO) of **1 c[•]**. The boron atom is indicated by an arrow.

radicals is still enhanced compared to that of **7[•]**.^[6] The **1 c[•]**/C₃H₇I interaction is almost 160 times lower than that of **1[•]**/C₃H₇I.

Molecular orbital calculations show that these N-heteroaryl-boryl radicals exhibit a planar π -type electronic structure (Figure 6). A significant spin delocalization from the boron atom into the ligand is found for the SOMO (see Figure 6 and the Supporting Information). A similar behavior has been recently found for NHC-boranes as well as N-heteroaryl-boranes which have a quite similar BDE(B-H) range.^[1,6,7,8b] The spin densities at the boron atom (S_B) were calculated as 0.215; 0.39; 0.355; 0.26; 0.5, 0.509 and 0.36 for **1 b[•]-e[•]** and **2 a, b[•]**, respectively (Figure 7; calculations at UB3LYP/6-31+G* level). For radicals **1 e[•]** and **b[•]**, most of the spin density is located over the heterocycle ring and, for at least one atom of the heterocycle, higher than

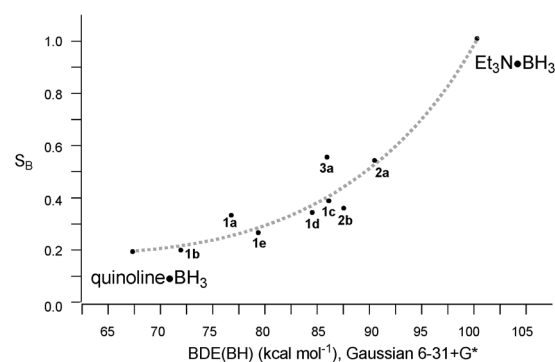


Figure 7. BDE(B-H) versus the spin density (S_B) on the boron atom for radicals **1 a-e**, **2 a, b** and **3 a**.

for the boron atom. Therefore, it can be expected that the reactivity of these radicals will be different from that of “true” boryl radicals which possesses the highest spin density on B (S_B). Such a behavior was previously studied through theoretical approaches.^[4c,5] Qualitatively, for the structures investigated here, the BDE(B-H) is correlated with the B atom spin density (S_B) in the radical (Figure 7), that is, upon an increase of the delocalization from the boron atom into the ligand, both S_B and BDE(B-H) are decreased. The data previously obtained for other ligated boranes are also added in Figure 7.^[7] Roughly, for BDE(B-H) < 80 kcal mol⁻¹, the highest spin density will not likely reside on the boron atom. This can also explain both the lowest reactivity of **1 b[•]** and **e[•]** in the reactions with MA and C₃H₇I and the excellent performance of **2 a** in radical dehalogenation reactions (vide infra).

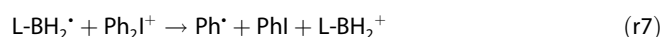
N-heterocycle-boryl radicals as new polymerization initiating structures

Some selected applications of the novel N-heterocycle-borane/additive couples as sources of boryl radicals were investigated, especially in thermal or photoinitiated polymerization processes. A quite similar efficiency was found for **1 c** and **d** (see the

Supporting Information); for the sake of clarity the results obtained for **1c** will be mainly presented here.

A thermal redox system based on the N-heterocycle–borane/Ph₂I⁺ combination

The combination of a N-heterocycle–borane with an oxidation agent (here an iodonium salt Ph₂I⁺) appears as an efficient initiating system for the free radical polymerization (FRP) of trimethylolpropane triacrylate (TMPTA) even at RT under air (Figure 8) that is, these polymerization reactions are highly exothermic. Using 3,5-dimethyl-1*H*-pyrazole/Ph₂I⁺, no polymerization is observed (Figure 8C, curve c) evidencing the fundamental role of the BH₃ complexation. The efficiency of these boranes decreases in the **1c** ≫ **1e** > **1b**, **2b** series (Figure S4 in the Supporting Information). Compound **1c** is characterized by the lowest oxidation potentials (−0.5 V/SCE; see Table 1) suggesting that a redox process can be involved (r5). In ESR–ST experiments, Ph[•] are clearly observed in the **1c**/Ph₂I⁺ system in full agreement with a reduction of the iodonium salt (PBN adduct: *a*_N = 14.4 G; *a*_H = 2.2 G; reference values in ref. [6]). Such a behavior has been also found for N-heteroaryl-boranes and the expected mechanism is probably similar to that recently proposed.^[6] The Ph[•] radical can 1) initiate the polymerization as in ref. [21] (r5) or 2) abstract a hydrogen atom from **1c** leading to the formation of a boryl radical (r6) which is further oxidized by Ph₂I⁺ (r7); then, a chain process with re-formation of Ph[•] occurs



This redox system can be also successfully applied to the cationic polymerization of an epoxy monomer (here: (3,4-epoxycyclohexane)methyl 3,4-epoxycyclohexylcarboxylate; EPOX–Uvacure 1500 from Cytec). Using **1c**/Ph₂I⁺ (2%/2% w/w), a complete polymerization is obtained at RT within 12 h. The cationic species **1c**⁺ (r5) and the borenium L-BH₂⁺ (r7) are the initiating species of the ring opening process.

A similar cationic polymerization can be also obtained using a different oxidation agent (AgSbF₆ instead of Ph₂I⁺) as the reduction of a silver salt by a pyridine–borane was already reported.^[22] With **1c**/AgSbF₆ (1%/1% w/w), a complete polymerization of EPOX is still obtained in 12 h at RT. The formation of the polyether network is easily observed at 1080 cm^{−1} (Figure S5 in the Supporting Information). The formation of Ag⁰ is well evidenced by UV–visible spectroscopy (Figure S5 in the Supporting Information): a new absorption band centered at about 400 nm appears in the film in the course of the polymerization process. This can be safely ascribed to the surface plasmon resonance (SPR) absorption band of the silver nanoparticles (NPs) as it has been previously reported in^[23] that unprotected Ag NPs in the < 15 nm size domain display a SPR band at 390 nm. By analogy with the results obtained above for the **1c**/Ph₂I⁺ system, this shows the initiating ability of the cationic

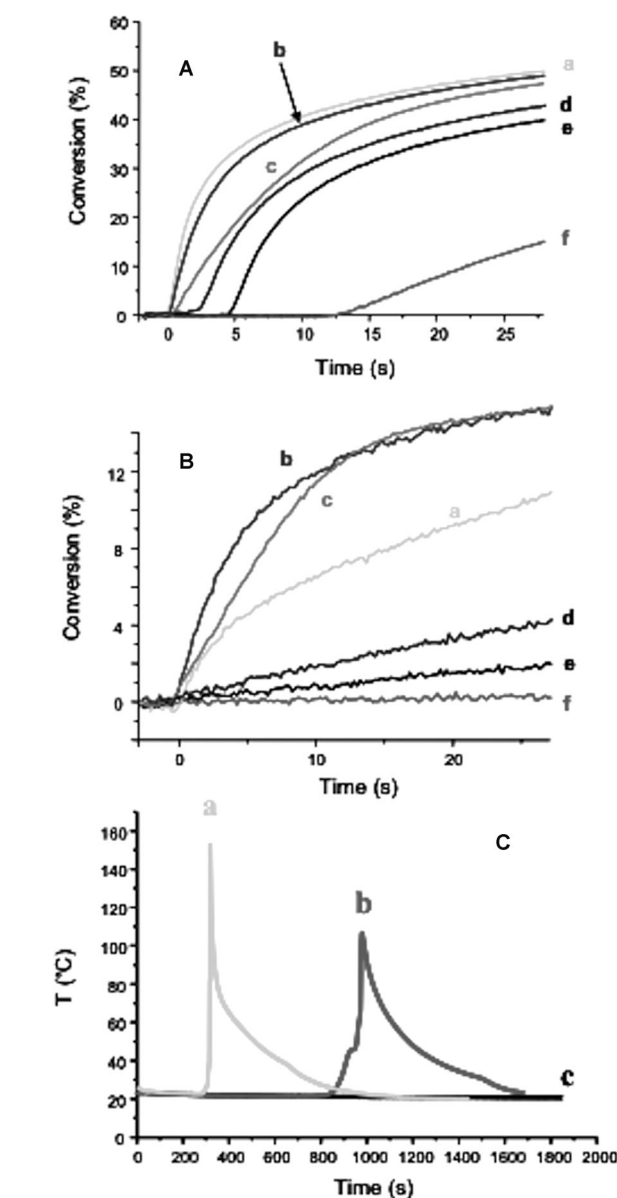
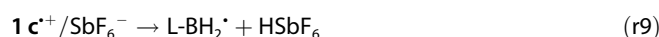


Figure 8. A) Photopolymerization profiles of TMPTA in laminate (irradiation Xe–Hg lamp) using various photoinitiating systems (1%/1% w/w or 1% w/w): a) BP/EDB; b) BP/**1c**; c) BP/**1e**; d) BP/**2b**; e) BP alone; f) **1c** alone. B) Photopolymerization profiles of TMPTA under air (irradiation Xe–Hg lamp) with for various photoinitiating systems (1%/1% w/w or 1% w/w): a) BP/EDB; b) BP/**1c**; c) BP/**1e**; d) BP/**2b**; e) BP alone; f) **1c** alone. C) Sample temperature versus time for the thermal polymerization of TMPTA initiated at RT by a) **1c**/Ph₂I⁺ (1%/1% w/w); b) **1c**/Ph₂I⁺ (0.5%/0.5% w/w); c) 3,5-dimethyl-1*H*-pyrazole **4c**/Ph₂I⁺ (1%/1% w/w); *t* = 0 corresponds to the addition of the borane complex to the reaction medium.

species generated. The oxidation of boryl radicals by silver salt (in r10 by analogy to r7) can also be expected since these species are characterized by a low ionization potential. An overall proposed mechanism can be proposed in (r8–10):

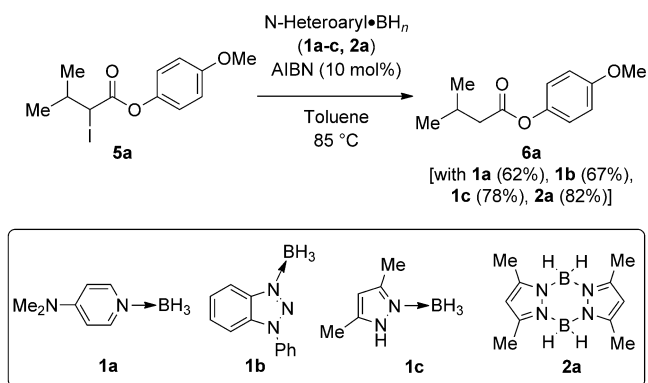


Boryl radicals as initiating structures in photoinitiating systems

The photoinduced FRP profiles of TMPTA using benzophenone (BP) as the photoinitiator in both the absence and the presence of the proposed boranes as co-initiators are shown in Figure 8. The addition of the borane complexes **1b–e** to BP drastically reduced the inhibition time and significantly enhanced the polymerization rates and the final conversions (Figure 8A, curves b–d and in the Supporting Information). This behavior is much more marked for polymerizations conducted under air (Figure 8B, curves b–d) where, without the borane, no polymerization is observed. Therefore, the present boryl radicals (**1b–e**) formed in (r4) are attractive initiating species, the ketyl radicals being unable to initiate a polymerization.^[21] This is in agreement with the high addition rate constants of boryl radicals to an acrylate unit reported above (e.g., MA in Table 2). The ability of **1b** to act as a co-initiator is very poor in line with its low reactivity in the addition reaction onto acrylate (see Table 2). Compound **1c** appears as the most promising co-initiator, even better than ethyl-dimethylaminobenzoate (EDB; which is a reference amine co-initiator).^[20c] It also exhibits the best performance for the FRP in laminate in agreement with a boryl radical quantum yield close to 1.0 and the highest addition rate constant to MA (Table 2).

N-heteroaryl-boryl radicals in dehalogenation reactions

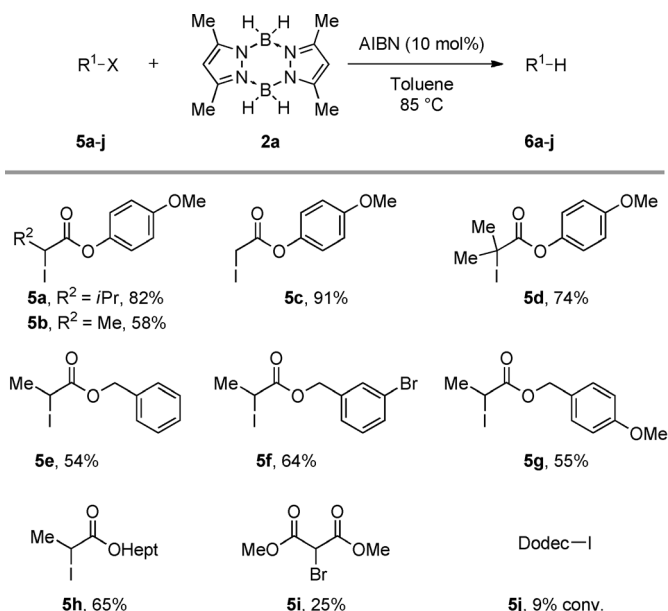
Besides the physical chemistry and photopolymerization studies of N-heteroaryl borane complexes, we investigated their use in synthetic organic chemistry and more precisely in dehalogenation reactions of a model substrate, α -iodo ester **5a**, in the presence of an initiator (10 mol%) in toluene at 85 °C (Scheme 2). A rapid screen of initiators such as oxygen, di-*tert*-butylperoxide, triethyl borane, and azobisisobutyronitrile (AIBN) revealed that the latter was convenient to use and led to reproducible results. A very rapid conversion of **5a** to the corresponding reduced species was observed in the case DMAP-BH₃ **1a** and N-phenylbenzotriazole-BH₃ **1b** (less than 10 min). However, only moderate yields were obtained (62–67%) due to the formation of a side product, *p*-methoxyphenol, that is certainly formed via the β -elimination of the radical intermediate. When pyrazole-BH₃ **1c** or pyrazabole **2a** were used, the amount of this side product was dramatically lowered and synthetically useful yields were obtained (78–82%).



Scheme 2. Initial screen of the boryl radical precursors for the dehalogenation reaction of α -iodoester **5a**.

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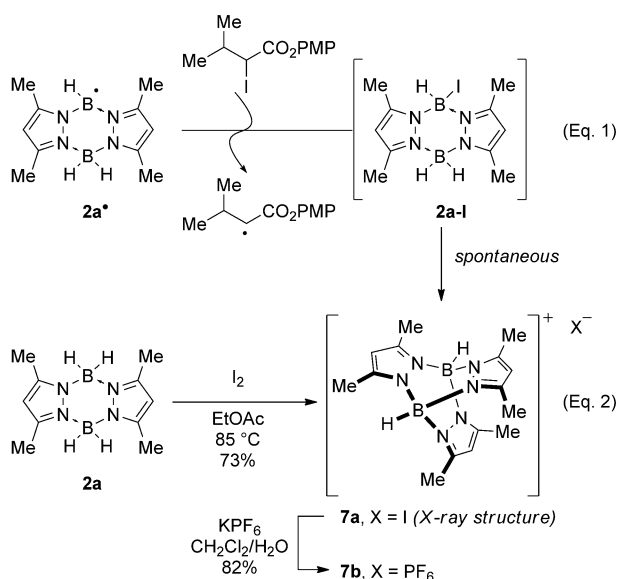
We next explored the scope of this dehalogenation reaction using pyrazabole **2a** as the most promising boryl radical precursor (Scheme 3). When the primary **5c**, secondary **5a**, **b** or



Scheme 3. Scope of the radical dehalogenation reaction of α -haloester **5a–j** using pyrazabole **2a**.

tertiary **5d** α -iodo esters were used, good yields of the corresponding dehalogenated products were obtained (91, 82, 58 and 74%, respectively). Various esters could also be employed in this transformation, such as benzyl esters **5e** (54%), **f** (64%), the bromine atom being untouched by the boryl radical in this case and *p*-methoxybenzyl ester **5g** (55%). Alkyl esters were also tolerated in this reaction, as shown by the clean dehalogenation of **5h** in 65% yield. Less efficient reaction partners were α -iodo Weinreb amides (not shown) or α -bromo esters. As an example, only 25% of the desired reduced product was obtained when bromo dimethylmalonate **5i** was used. Eventually, as could be expected from a polarity point of view, the dehalogenation of dodecyl iodide **5j** by the electron-rich boryl radical **2a** was not efficient and only 9% conversion of the corresponding dodecane was obtained (Scheme 3).

Experimentally, a white precipitate was formed almost immediately in the deep red reaction mixture when the dehalogenation was conducted with pyrazabole **2a**. After filtration and recrystallization of this stable solid, X-ray crystallographic studies demonstrated that this precipitate was the boronium salt^[24] derivative **7a** (CCDC 981832; B–H 1.056 Å), with iodine as the counter-anion (Scheme 4 and Figure 9). We surmised that this borocation **7a** is formed spontaneously from the iodo-pyrazabole **2a–l**, a hypothesis that was supported by direct iodolysis studies of **2a**.^[25] After extensive optimization, it



Scheme 4. Synthesis of the boronium salt **7a**, byproduct of the dehalogenation reaction (Eq. 1) and its de novo synthesis (Eq. 2).

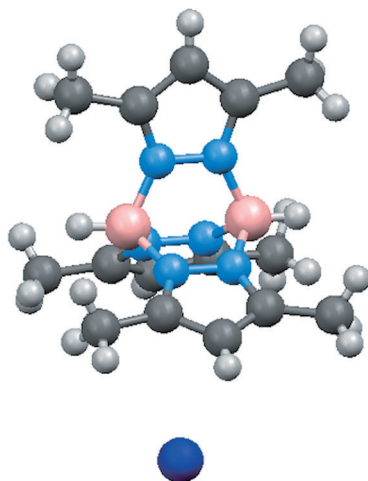
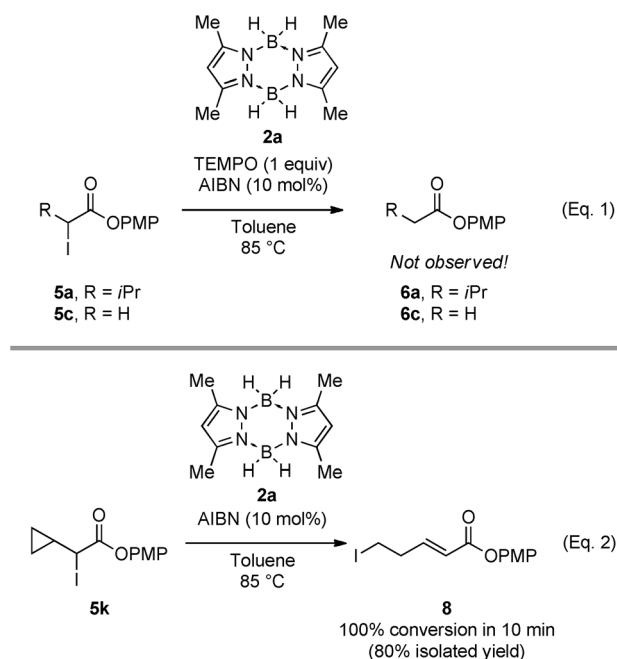


Figure 9. X-ray structure of diboracation **7a** (CCDC 981832).

was found that iodolysis of **2a** was best conducted in ethyl acetate at 85 °C, the boronium salt **7a** thus being obtained in 74% yield on a multigram scale. It should also be noted that the iodine counter-anion could be exchanged for a hexafluorophosphate (**7b**, 82%), thus further improving its stability. The reactivity of this diboracation as an initiator in polymerization reactions is currently under investigations.

To gain insights into the radical nature of these dehalogenation reactions, several control experiments were conducted (Scheme 5). In a first set of reactions, TEMPO (1 equivalent) was used as a radical inhibitor of the dehalogenation reaction of **5a** and **c** (Eq. 1). No conversion was observed, giving a first hint of a radical reaction. Next, the radical clock^[26] substrate **5k** (Eq. 2) featuring a α -iodo- α -cyclopropyl motif was prepared in two steps from commercially available cyclopropylacetic acid by esterification with *p*-methoxyphenol followed by lithiation



Scheme 5. Control experiments of the dehalogenation reaction using a radical scavenger (Eq. 1) and a radical clock process (Eq. 2).

and iodolysis of the lithium enolate intermediate. Heating of **5k** at 85 °C in toluene (in the absence of N-heteroaryl borane complexes and radical initiators) led to the complete recovery of the starting material. Eventually, combination of pyrazabole **2a** (0.5 equivalent; or DMAP-BH₃ **1a**, not shown) and AIBN (10 mol%) led to a very fast reaction, the δ -iodo- α,β -unsaturated ester **8** being isolated as the only product in 80% yield in only 10 min. The formation of this compound could be explained by the ring-opening of an α -cyclopropyl radical followed by the trapping of the primary radical by an iodine atom, either from the starting material **5k** or an intermediate such as **2a-I** (Scheme 4). We also checked that the boronium salt **7a** was not an efficient reaction partner, since only traces of **8** were obtained under these reaction conditions (not shown). All together, these results clearly point towards a radical dehalogenation reaction, in full agreement with the physical studies conducted in parallel (vide supra).

Conclusion

In this article, a new class of radicals derived from N-heteroaryl-boranes such as pyrazole-boranes and pyrazaboles was presented. The synthesis, characterization, and the associated reactivity of these radicals were investigated. Interestingly, a high modulation of the BDE(B-H) through the choice of the N-heteroaryl moiety was noted (BDE in the 70.8–91.3 kcal mol⁻¹ range) which could be correlated with the spin density on the boron atom in the corresponding radical. High rate constants of boryl radical formation through a hydrogen abstraction in *t*BuO[•]/borane couples were determined, in agreement with these low BDEs(B-H). The implications on the reactivity of these boryls are important since the addition rate constants

span over at least two orders of magnitude. Relevant applications in polymer science and synthetic organic chemistry were also provided, outlining the high lability of these B–H bonds as well as the excellent reactivity of the corresponding boryl radicals.

Experimental Section

Benzophenone (BP) was used as model photoinitiator (from Aldrich). Ethyl dimethylaminobenzoate (EDB; Esacure EDB from Lambert) was chosen as a reference amine co-initiator. Methylacrylate (MA), vinylacetate (VA), ethylvinylether (EVE), diphenyl iodonium hexafluorophosphate (Ph_2I^+), iodopropane, 4-phenyl-1-butene were obtained from Aldrich with the highest purity available. CCDC 981830 (**2a**), 981831 (**2b**), 981833 (**3a**) and 981832 (**7a**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Laser flash photolysis experiments

Nanosecond laser flash photolysis (LFP) experiments were carried out using a Q-switched nanosecond Nd/YAG laser ($\lambda_{\text{exc}} = 355 \text{ nm}$, 9 ns pulses; energy reduced down to 10 mJ, from Minilite Continuum) and an analyzing system consisting of a ceramic xenon lamp, a monochromator, a fast photomultiplier and a transient digitizer (Luzchem LFP 212).^[9]

ESR spin trapping experiments

The radicals were generated under the polychromatic light exposure of a Xe–Hg lamp (Hamamatsu, L8252, 150 W) of N-heterocycle–borane in di-*tert*-butyl peroxide/*tert*-butylbenzene (a small amount of acetonitrile is also added to ensure a good solubility). The generated radicals were trapped by phenyl-*N-tert*-butylnitron (PBN). The ESR spectra simulations were carried out with the WINSIM software.^[10] The procedure used has been presented in detail in ref. [6]. The ESR spectrum simulation includes ^{10}B as mentioned in ref. [2d] and [2f].

Redox potentials

The redox potentials (E_{ox} vs. SCE) were measured in acetonitrile by cyclic voltammetry with tetrabutyl-ammonium hexafluorophosphate 0.1 M as a supporting electrolyte (Voltalab 06-Radiometer; the working electrode was a platinum disk and the reference a saturated calomel electrode-SCE). Ferrocene was used as a reference ($E_{\text{ox}} = +0.44 \text{ V/SCE}$).

DFT calculations

All the calculations were performed by using the hybrid functional B3LYP from the Gaussian 03 suite of program.^[11] Reactants and products were fully optimized at the B3LYP/6-31+G* level (checked for imaginary frequencies) for the calculations of the different reaction enthalpies (ΔH_r). The selected DFT method exhibits a relatively good performance for the BDE calculations (see refs. [6] and [7]). The calculated BDEs are also very similar to those extracted from the calculations using isodesmic reactions (see ref. [7]). Adiabatic ionization potentials (IP) were calculated from the energy difference between the relaxed neutral molecule and the relaxed ion (B3LYP/6-31+G* level). The transition states (TS) were calculated with DFT methods (UB3LYP/6-31+G* level) using

a QST2 approach. The TSs were frequency checked. The charge transfer from the radical to the alkene was evaluated from the Mulliken analysis of the TS.

Photopolymerization experiments

For film polymerization experiments, a photoinitiating system was dissolved into a bulk formulation based on trimethylolpropane triacrylate (TMPTA from Cytec).^[12] The formulations sandwiched between two polypropylene films (20 μm thick) were deposited on a BaF_2 pellet and irradiated with polychromatic light (Xe–Hg lamp, Hamamatsu, L8252, 150 W). The evolution of the double bond content was followed by real-time FTIR spectroscopy (Nexus 870, Nicolet) at room temperature. These experiments were carried out both in laminate and under air.^[12d] Compared to the N-heteroarylboranes previously investigated (such as **1a**), an excellent solubility was found for **1b–e** and **2a,b** in classical organic solvents. It should be noted that a slightly turbid solution (albeit stable) was noted in TMPTA for **2b**.

Thermal polymerization experiments

The polymerization was carried out in pill-box for a sample of 1 g. The progress of the exothermic polymerization was followed by monitoring the sample temperature using a method presented in detail in.^[13] The addition of the organoboranes into the formulation corresponds to time $t = 0 \text{ s}$.

Acknowledgements

The authors thank the CNRS, the University of Haute-Alsace, the University of Strasbourg, the Agence Nationale de la Recherche (ANR BLAN-0802, ANR SILICIUM) and the Institut Universitaire de France for financial support.

Keywords: boryl radicals • co-initiator • dehalogenation • N-heterocycle–boranes • polymerization • radical chemistry

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Received: January 17, 2014

Published online on March 13, 2014