JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Article

pubs.acs.org/JACS

Mechanistic and Preparative Studies of Radical Chain Homolytic Substitution Reactions of N-Heterocyclic Carbene Boranes and Disulfides

Xiangcheng Pan,[†] Anne-Laure Vallet,[‡] Stéphane Schweizer,[§] Karim Dahbi,[§] Bernard Delpech,[‡] Nicolas Blanchard,[§] Bernadette Graff,[⊥] Steven J. Geib,[†] Dennis P. Curran,*[,†] Jacques Lalevée,*[,⊥] and Emmanuel Lacôte*[,‡,∥]

[†]Department of Chemistry, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, United States

[‡]ICSN CNRS, Avenue de la Terrasse, 91198 Gif-sur-Yvette Cedex, France

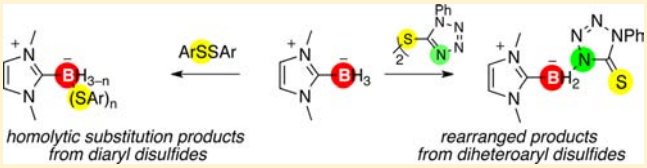
[§]Université de Strasbourg, Laboratoire de Chimie Moléculaire, CNRS UMR 7509, ECPM, 25 rue Becquerel, 67087 Strasbourg, France

[⊥]Institut de Science des Matériaux de Mulhouse, IS2M-UMR CNRS 7361-UHA, 15 rue Jean Starcky, 68057 Mulhouse Cedex, France

[∥]Université de Lyon, Institut de chimie de Lyon, UMR 5265 CNRS-Université Lyon I-ESCPE Lyon, 43 Bd du 11 novembre 1918, 69616 Villeurbanne Cedex, France

Supporting Information

ABSTRACT: Reactions of 1,3-dimethylimidazol-2-ylidene−borane (diMe-Imd-BH_3) and related NHC−boranes with diaryl and diheteroaryl disulfides provide diverse NHC−boryl monosulfides (diMe-Imd-BH_2SAr) and NHC−boryl disulfides (diMe-Imd-$BH(SAr)_2$). Heating in the dark with 1 equiv of disulfide favors monosulfide formation, while irradiation with 2 equiv disulfide favors disulfide formation. With heteroaryl disulfides, the NHC−borane in the primary NHC−boryl sulfide product migrates from sulfur to nitrogen to give new products with a thioamide substructure. Most substitution reactions are thought to proceed through radical chains in which homolytic substitution of a disulfide by an NHC−boryl radical is a key step. However, with electrophilic disulfides under dark conditions, a competing ionic path may also be possible.



INTRODUCTION

The element boron has a rich history in radical chemistry because it participates in a wide assortment of radical−molecule reactions. In the vast majority of these reactions, boron is in the molecule component of the pair. For example, boranes (BR_3) have a broadly useful homolytic substitution chemistry, reacting with all sorts of oxygen, nitrogen, and sulfur and halogen radicals (X•) to expel carbon radicals (R•) (eq 1).[1] Today triethylborane and related boranes are among the most common initiators[2] and reagents[3] in synthetic radical chemistry.

$$X^{\bullet} + BR_3 \rightarrow XBR_2 + R^{\bullet} \quad (1)$$

Homolytic substitution reactions with boron as the radical component of the pair are much less common. This dearth of information is at least in part because there are so few classes of boron-centered radicals. The study of neutral boryl radicals was pioneered by Roberts and co-workers. Amine−boryl radicals have been the most well studied, and they abstract univalent atoms such as iodine, bromine, and even hydrogen if the polarity is matched.[4] There is a small amount of information on phosphine−boryl radicals,[4e−g] and some boryl radical anions and radical cations are known.[5] The spin density is at least partially delocalized onto boron in a variety of radicals and radical ions, including conjugated boranes and clusters.[6] This collection pales in comparison to the encyclopedia of information on radicals centered on boron's neighboring elements to the right in the second row of the periodic table (C, N, O).[7] Homolytic substitutions at divalent elements such as sulfur are core reactions of many types of radicals, including silicon, tin, and carbon.[8]

Radicals derived from N-heterocyclic carbene−boranes (NHC−boranes) are now contributing a new chapter to the chemistry of boron-centered radicals.[9] NHC complexes of the parent borane (NHC−BH_3) are readily available, stable solids that are conveniently prepared and handled.[10] One of the hallmark features of NHC−boranes is a relatively weak B−H bond,[9b,11] cleavage of which gives an NHC−boryl radical (NHC−BH_2•).[12]

Reactions of NHC−boryl radicals are summarized in Figure 1. These radicals add to xanthates[9a,b] (which triggers deoxygenation) and to electron-poor alkenes (which triggers polymerization).[12] They also abstract bromine and iodine from

Received: April 15, 2013
Published: May 29, 2013

ACS Publications © 2013 American Chemical Society

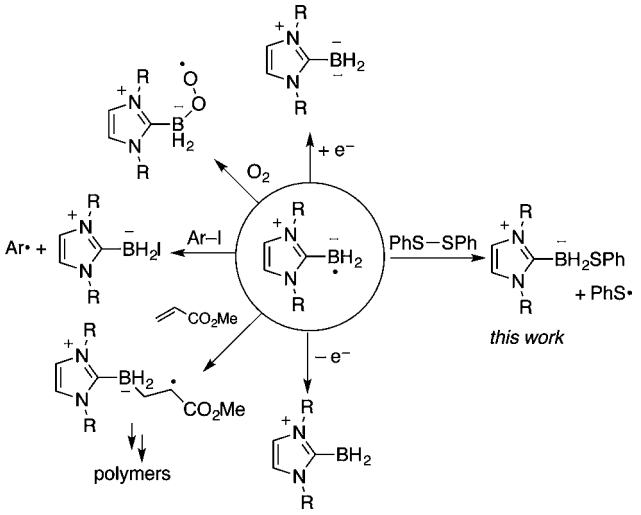


Figure 1. Elementary reactions of NHC–boryl radicals: (left) recently reported; (right) this work.

alkyl[12c] and even aryl halides.[14] They react quickly with O_2[12a,b,d] and can be oxidized relatively easily to borenium ions.[12a,b,d,15] They can also be reduced with difficulty to boryl anions.[16] Preparatively, NHC–boranes are emerging as useful reductants in small molecule radical chemistry[13,14,17] and as coinitiators in polymer chemistry.[18]

The discovery of this rich vein of NHC–boryl radical chemistry offers encouragement that more new reactions remain as yet untapped. Among these, homolytic substitution of a divalent element is an important elementary radical step[8] that has not been observed with NHC–boryl radicals.

Here we describe preparative and mechanistic aspects of substitution reactions of NHC–boranes with disulfides to give stable NHC–boryl sulfides. Mono- and disubstituted products are formed selectively in good yields depending on the reaction conditions. Reactions conducted in the presence of light occur by radical chains in which a key step is rapid homolytic substitution of a disulfide by an NHC–boryl radical. Certain heterocyclic boryl sulfide products undergo a rapid 1,3-boryl shift from S to N to give stable new NHC–boranes with B–N-heterocycle bonds.

RESULTS AND DISCUSSION

Discovery of Homolytic Substitution at Sulfur. Evidence for the viability of the homolytic substitution reaction in Figure 1 first came from an unexpected quarter. During the course of kinetic experiments to measure the rate constant of the reaction of phenylthiyl radical (PhS•) with the typical NHC–borane **1**,[14] we discovered that the apparent lifetime of the phenylthiyl radical in the presence of **1** was affected by the presence of oxygen.

In these laser flash photolysis (LFP) experiments (Figure 2), solutions of 1,3-dimethylimidazol-2-ylidene–borane (diMe-Imd–BH_3 or **1**) and diphenyl disulfide (PhSSPh) were irradiated at wavelengths suitable for generation of the phenylthiyl radical. This radical absorbs at 480 nm; therefore, its decline in concentration over time is easily monitored. The effect of oxygen is illustrated in Figure 2 for two typical reactions between PhSSPh and **1** at 0.027 M in ethylbenzene/acetonitrile. The lifetime of PhS• in air (trace 1) is dramatically reduced compared to that under argon (trace 2).

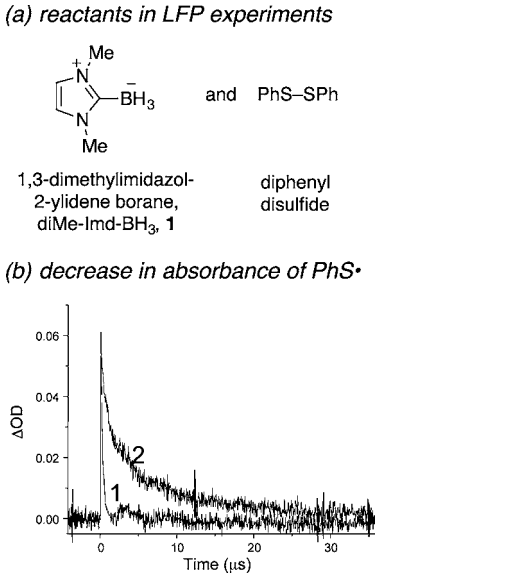


Figure 2. (a) Reactants in LFP experiments, in ethylbenzene/acetonitrile with [**1**] = 0.027 M. (b) Decay of PhS• over time (1) in air and (2) under argon. The change in optical density at 480 nm is plotted.

At first glance, this decrease seems surprising because PhS• does not react quickly with oxygen ($k < 10^6$ M^{-1} s^{-1}). However, the effect can be understood by considering the elementary reactions in Figure 3. Step 1, abstraction of hydrogen from **1** by

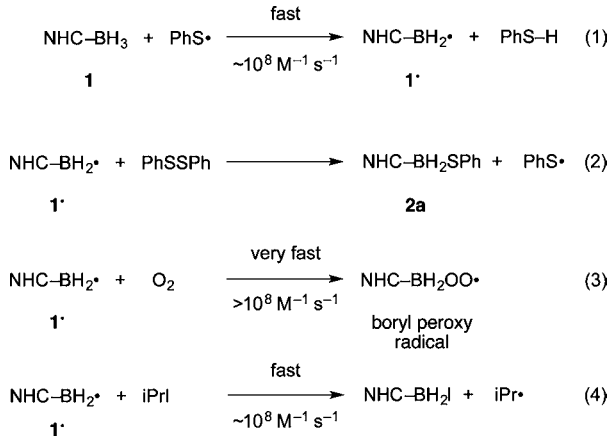


Figure 3. LFP experiments revealing a chain reaction that prolongs the apparent lifetime of phenylthiyl radical (steps 1 and 2) but is shut down by oxygen (step 3) or isopropyl iodide (step 4).

PhS•, is the reaction whose rate constant we had targeted for measurement. This was ultimately determined to be a fast reaction ($k \approx 10^8$ mol^{-1} s^{-1}).[14] Now assume that the resulting NHC–boryl radical **1**• reacts quickly with diphenyl disulfide by homolytic substitution, as shown in step 2. This provides the *B*-thiophenyl borane **2a** (NHC–BH_2SPh) and returns another phenylthiyl radical. Together, steps 1 and 2 are a chain that prolongs the apparent lifetime of PhS•.

We suggest that the introduction of O_2 disrupts this chain not by reacting with PhS• but by reacting with NHC–boryl radical **1**•. Step 3 becomes faster than step 2, the prolongation effect of the chain is turned off, and the apparent lifetime of PhS• goes down. Thus, the addition of O_2 revealed a chain that was otherwise hidden. In effect, the O_2 does not (directly)

dx.doi.org/10.1021/ja403627k | J. Am. Chem. Soc. 2013, 135, 10484–10491

decrease the lifetime of PhS•. Instead, the NHC−borane prolongs the lifetime of PhS• and O_2 suppresses the prolongation.

If the mechanism in Figure 3 is correct, then the observed decrease in apparent lifetime of PhS• should not be limited to O_2. To test this idea, we conducted a pair of experiments under argon with and without added isopropyl iodide (iPrI). Like O_2, isopropyl iodide reacts slowly with PhS• but rapidly with boryl radical **1**• (step 4, $k_I \approx 10^8$ mol^{-1} s^{-1}).[12c] In addition, like O_2, isopropyl iodide dramatically decreased the apparent lifetime of PhS• in LFP experiments (see data in the Supporting Information).

The chain comprised of steps 1 and 2 must be kinetically viable (under the LFP conditions, at least), but it has unclear thermodynamics. On the basis of the relevant S−H[19] and B−H[11,12] bond dissociation energies (BDEs), step 1 is roughly thermoneutral (about ±3 kcal/mol). (However, the polarity is favorable for a fast reaction because boryls and thiyls are nucleophilic and electrophilic, respectively.[14]) Therefore, the overall thermodynamics is staked on step 2. We calculated the BDE change for this step at the UB3LYP/6-31+G* level (see Figure 4) and found that it is highly exothermic ($\Delta H°$ = −18 kcal mol^{-1}). Likewise, the corresponding second substitution of **2a**• to give NHC−BH(SPh)$_2$ **3a** is highly exothermic ($\Delta H°$ = −15 kcal mol^{-1}), while the third and final substitution of **3a**• to give NHC−B(SPh)$_3$ **4a** is less so ($\Delta H°$ = −7 kcal mol^{-1}). Taken together, the LFP results and the calculations support the notion that NHC−boranes will react preparatively with disulfides to give boryl sulfides.

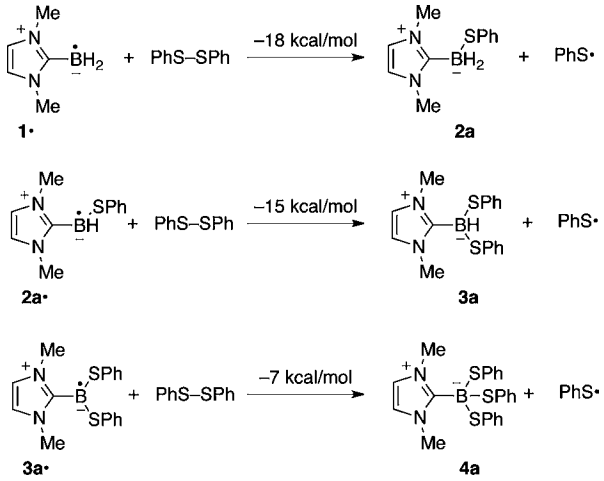
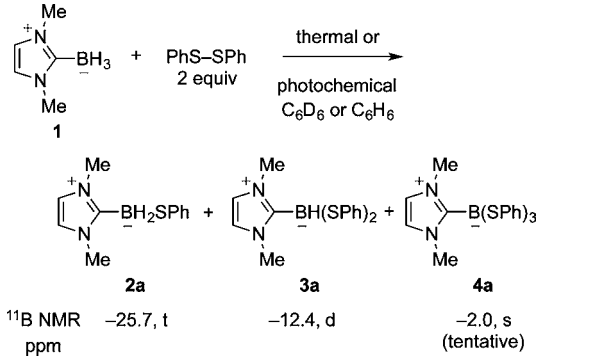


Figure 4. Change in enthalpy ($\Delta H°$) of sequential homolytic substitution reactions of NHC−boryl radicals **1**•, **2a**•, and **3a**•.

Preparative Experiments. We started with a series of scouting experiments to identify reaction conditions and to characterize products. These reactions were conducted in NMR tubes with 1 equiv of **1** and 2 equiv of PhSSPh and were followed by ^{11}B NMR spectroscopy. Soon we learned that **2a**−**4a** exhibit a triplet (−25.7 ppm, J_{B-H} = 101 Hz), a doublet (−12.4 ppm, J_{B-H} = 121 Hz), and a singlet (−2.0 ppm), respectively. NHC−boranes react with strong acids and assorted electrophiles;[20] therefore, their reactions with diphenyl disulfide could in principle occur by either ionic or radical mechanisms. Accordingly, reactions were conducted in NMR tubes shielded by aluminum foil (dark) or exposed to ambient laboratory light or light from a sunlamp. The results are summarized in Table 1.

Table 1. Homolytic Substitution Reactions of NHC−Borane 1 and PhS−SPh



entry	conditions[a]	temp, °C	time	amt of **2a**, %[b]	amt of **3a**, %[b]	isolated yield, %[c]
1	dark	25	4 days	81	19	
2	lab light	25	2.5 h	83[d]	16	
3	lab light	55	1.3 h	67	33	
4	sunlamp	30	10 min	0	100	
5[e]	dark	45	6 h	83	17	84[f]
6	sunlamp	60	1 h	0	100	80

[a]0.2 M **1** and 2 equiv of PhSSPh in C_6D_6. [b]Ratio determined by ^{11}B NMR spectroscopy without a standard. [c]Isolated by flash chromatography. [d]With 1% remaining **1**. [e]1 equiv PhSSPh used. [f]A 5/1 mixture of **2a** and **3a**.

In a typical dark experiment with 2 equiv of PhSSPh at 25 °C, **1** was gradually consumed over 4 days to give 81% of **2a** and 19% of **3a** (entry 1). The rates of the dark experiments at room temperature were somewhat variable. For example, in experiments similar to entry 1 but stopped after only 2 h, conversions to **2a** varied from <5 to 18% (no **3a** was detected at this short time). The dark reactions at room temperature are slow, and initiation by stray light may be a factor in reaction rates.

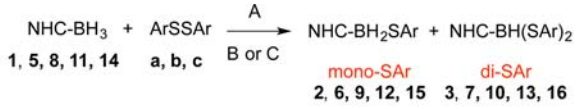
Indeed, a similar reaction at room temperature but exposed to ambient laboratory light gave 83% of **2a** and 16% of **3a** after only 2.5 h (entry 2; a trace (1%) of unreacted **1a** remained). On further reaction, the amount of the double-substitution product **3a** increased at the expense of **2a**. An even faster reaction occurred on heating at 55 °C (entry 3), providing 67% of **2a** and 33% of **3a** after 1.3 h. The results in entries 1−3 illustrate the general problem that **2a** and **3a** are formed competitively especially (but not only) during irradiation. Irradiation with a 275 W sunlamp dramatically increased the conversion (entry 4), and now disulfide **3a** was the sole product after only 10 min of irradiation at 30 °C.

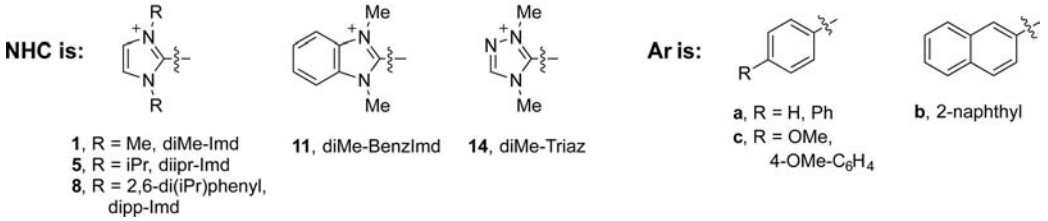
NHC−boryl trisulfide **4a** was not detected in any of these experiments with 2 equiv of PhS−SPh, and it was only formed in small amounts in an experiment with 3 equiv. However, sunlamp irradiation of **1** with a large excess of PhS−SPh (10 equiv) finally gave the large singlet at −2.0 ppm that we assign to **4a**. Unlike **2a** and **3a** (see below), boron trisulfide **4a** did not survive flash chromatography. Therefore, this assignment is tentative.

We next conducted two preparative experiments under conditions that previewed the subsequent scope study. In the thermal experiment (entry 5) targeting monosulfide **2a**, a

dx.doi.org/10.1021/ja403627k | J. Am. Chem. Soc. 2013, 135, 10484−10491

Table 2. Scope of the Homolytic Substitutions Leading to NHC−Boryl Sulfides





entry	NHC	Ar	conditions[a]	reaction time, h	mono-SAr; yield, %	di-SAr; yield, %
1	diMe-Imd	2-naphthyl	A	1.5	**2b**; 86	**3b**; 10
2	diMe-Imd	2-naphthyl	B[b,c]	72		**3b**; 86
3	diMe-Imd	2-naphthyl	C	0.25		**3b**; 100[d]
4	diMe-Imd	4-MeO-C_6H_4	A	1	**2c**; 76	**3c**; 24
5	diMe-Imd	4-MeO-C_6H_4	B[b,c]	72		**3c**; 82
6	diMe-Imd	4-MeO-C_6H_4	C	0.5		**3c**; 91
7	diiPr-Imd	Ph	A[b]	48	**6a**; 66	**7a**; 5
8	diiPr-Imd	Ph	B	4		**7a**; 72
9	dipp-Imd	Ph	A	48	**9a**; 36[e]	**10a**; 14[e]
10	dipp-Imd	Ph	B	10		**10a**; 45
11	dipp-Imd	4-MeO-C_6H_4	A	2	**9c**; 28	
12	dipp-Imd	4-MeO-C_6H_4	C	2		**10c**; 35
13	diMe-BenzImd	Ph	A	1.5	**12a**; 52	**13a**; 19
14	diMe-BenzImd	Ph	C	0.5		**13a**; 68
15	diMe-BenzImd	2-naphthyl	A	2	**12b**; 48	
16	diMe-BenzImd	2-naphthyl	B[b,c]	16		**13b**; 70
17	diMe-BenzImd	4-MeO-C_6H_4	A	2	**12c**; 40	
18	diMe-BenzImd	4-MeO-C_6H_4	C	0.5		**13c**; 95
19	diMe-Triaz	Ph	A	6	**15a**; 43	**16a**; 9
20	diMe-Triaz	Ph	B	1		**16a**; 85
21	diMe-Triaz	2-naphthyl	A	2	**15b**; 40	
22	diMe-Triaz	2-naphthyl	C	0.5	**15b**; 2	**16b**; 55
23	diMe-Triaz	4-MeO-C_6H_4	A	2	**15c**; 60[f]	**16c**; 24[f]
24	diMe-Triaz	4-MeO-C_6H_4	C	0.5		**16c**; 54

[a]Conditions: (A) PhSSPh (1 equiv), PhH, 45 °C; (B) PhSSPh (2 equiv), PhH, sunlamp 275 W, room temperature to 60 °C; (C) PhSSPh (2 equiv), PhH, OmniCure, room temperature to 40 °C. [b]Reaction was carried out at room temperature. [c]The reaction was exposed to laboratory light (no lamp). [d]NMR yield. [e]Inseparable mixture, isolated together with 11% of remaining starting material. [f]4% of SM was also isolated.

solution of 1 equiv of **1** and only 1 equiv of PhSSPh was heated at 45 °C for 6 h. Purification by flash chromatography provided an inseparable mixture of **2a** and **3a** in 84% yield in a ratio of 83/17. In the photochemical experiment targeting boryl disulfide **3a**, 1 equiv of **1** and 2 equiv of PhSSPh were irradiated at 60 °C for 1 h. This gave full conversion of **1**, and pure **3a** was isolated in 80% yield. Both **2a** and **3a** were stable compounds that were fully characterized by the usual means, including ^{1}H, ^{13}C, and ^{11}B NMR spectroscopy and MS (see the Supporting Information).

Table 2 presents the scope of these reactions for the preparation of both NHC−boryl mono-sulfides and bis-sulfides. We looked for selective formation of NHC−boryl monosulfides under dark conditions and for formation of NHC−boryl disulfides under light conditions. In the dark reactions (conditions A), the NHC−borane and 1 equiv of diphenyl disulfide were warmed in benzene at 45 °C in a flask protected with aluminum foil. In the light reactions, the NHC−borane was reacted with 2 equiv of diphenyl disulfide in benzene under irradiation from either a sunlamp (conditions B) or an OmniCure lamp (conditions C). The lamps (especially the sunlamp) generate some heat, and the temperatures of these reactions are estimated to be 40−60 °C.

The reactions with diMe-Imd−BH_3 **1** were successfully extended to dinaphthyl disulfide **b** and bis(4-methoxyphenyl) disulfide **c** (Table 2, entries 1−6). Good yields of monosulfides **2b,c** (86% and 76%) were obtained under the thermal conditions A (entries 1 and 4). Minor amounts of boryl disulfide products **3b,c** (10% and 24%) were also isolated by flash chromatography. In contrast to the pair in Table 1, this and all the other pairs of boryl mono- and disulfides in Table 2 were separable and were isolated in pure form. Under the light conditions (B and C), the corresponding boryl disulfides **3b,c** were formed in good yields (82−91%, entries 2, 3, 5, and 6) with little or no accompanying monosulfides.

Larger imidazolylidene-derived NHC−boranes were examined next. Reactions with diiPr-Imd−BH_3 **5** and diphenyl disulfide **a** led to either monosulfide **6a** (entry 7, dark) or

dx.doi.org/10.1021/ja403627k | J. Am. Chem. Soc. 2013, 135, 10484−10491

disulfide **7a** (entry 8, light) selectively and in good yields (**6a**, 66%; **7a**, 72%); however, the dark reaction to give **6a** was much slower (48 h compared to 4 h). The reactions of dipp-Imd–BH_3 **8** with disulfides **a** and **c** were less efficient and gave lower isolated yields of both boryl mono- and disulfides (**9a**, 36%; **10a**, 45%; **9c**, 28%; **10c**, 35%; entries 9–12). Product **9a** was identical with a sample prepared by nucleophilic substitution of dipp-Imd–BH_2(OTf) with lithium benzenethiolate.[20]

We then examined the benzo-fused NHCs derived from benzimidazole–borane **11** (diMe-BenzImd–BH_3) with all three disulfides (entries 13–18). The monosulfides **12a–c** were obtained under the dark conditions in 40–52% isolated yields, usually with good mono/di selectivities (entries 13, 15, and 17). Conversely, the boryl disulfides **13a–c** were isolated in better yields (68–95%) under the light conditions (entries 14, 16, and 18). The reactions of triazolylidene–borane **14** (diMe-Triaz–BH_3) with disulfides **a** and **b** (entries 19–24) continued this trend. Moderate yields of monosulfides (**15a**,**b**, 40% and 43%) were obtained under the dark conditions, while better yields of boryl disulfides (**16a**,**b**, 85% and 55%) were obtained under the light conditions. Only in the pair of reactions of **14** with **c** (entries 23 and 24) was the boryl monosulfide (**15c**, 60%) isolated in better yield than the boryl disulfide (**16c**, 54%).

Overall it appears that the substitution reactions are general and tolerate changes in the NHC–borane and the disulfide. The dark reactions with 1 equiv of disulfide ArSSAr give the boryl monosulfide NHC–BH_2SAr selectively but usually not exclusively. The two products can be separated by flash chromatography (except for **2a** and **3a**). The light conditions with 2 equiv of disulfide ArSSAr give faster reactions and higher yields, producing only the boryl disulfide NHC–BH$(SAr)_2$. Substrates derived from hindered or less nucleophilic carbenes (for example the benzimidazolylidene[21]) seem to fare better under light conditions B or C compared to dark conditions A.

We also briefly investigated other solvents for these reactions, because benzene is not a preferred solvent for larger scale reactions. Several preparative reactions from Table 2 were conducted in both toluene ($C_6H_5CH_3$) and benzotrifluoride ($C_6H_5CF_3$),[22] and these gave yields comparable to those for the reactions in benzene (see the Supporting Information).

Most of the boryl sulfide and disulfide products in Table 2 are white solids, though a few are viscous oils. The crystal structure of the representative disulfide diMe-Imd–BH(S-2-naphthyl)$_2$ **3c** is shown on the left side of Figure 5. The B–H bond of **3c** is approximately in the plane of the imidazole ring. The pair of *S*-2-naphthyl groups form a cavity above and below this B–H bond on each side.

Discovery of a 1,3-Boryl Shift from S to N. We also surveyed the reactions of the NHC–boranes with two common bis(heteroaryl) disulfides. The reaction of mercaptobenzothiazolyl disulfide **17** with NHC–borane **1** under the light conditions delivered surprises that are shown in Scheme 1. The product distribution depended on how many equivalents of disulfide **17** were added.

During sunlamp irradiation under the usual conditions B but with only 1 equiv of **17** (Scheme 1a), a new triplet consistent with expected boryl sulfide **18** appeared in the ^{11}B NMR spectrum of the reaction mixture at −24 ppm. As usual, this triplet started to disappear before all of **1** was consumed; however, it was not replaced by the doublet that was seen under light conditions, where boryl sulfides are converted to boryl disulfides. Instead, it was replaced by another triplet at −20 ppm that remained intact for the duration of the irradiation.

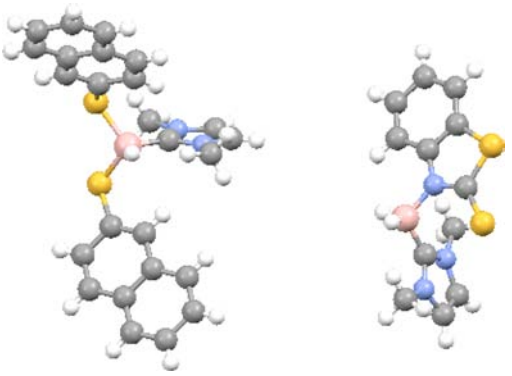
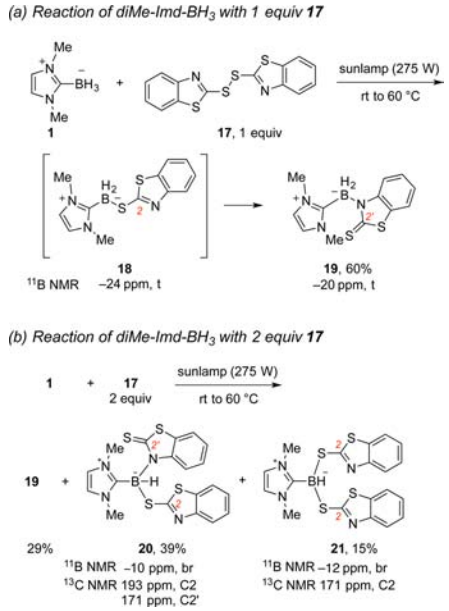


Figure 5. Representative X-ray crystal structures: (left) dinaphthyl sulfide **3c** from Table 2; (right) 1,3-boryl shift product **19** from Scheme 1. Boron is shaded pink.

Scheme 1. (a) 1,3-Shift of the Boron from Sulfur to Nitrogen of a Primary Boryl Sulfide Product and (b) Formation of Symmetrical and Unsymmetrical Bis-Adducts



This final product was purified by chromatography (60%) and then crystallized. The X-ray structure (see Figure 5, right side) showed that the stable product was NHC–boryl benzo[*d*]thiazole-2(3*H*)-thione **19**, which features a B–N single bond and a C=S double bond. The resonance at 192 ppm in the ^{13}C NMR spectrum was assigned to the carbon atom of the C=S double bond of **19** (C2′). Evidently, the primary product is indeed the boryl sulfide **18** with a B–S single bond and a C=N double bond, but this rearranges rather easily, formally by a 1,3-boryl shift from S to N, to give **19**.

The rearranged *N*-boryl adduct **19** is at least distantly related to various *N*-boryl triazoles and tetrazoles that have been made by dipolar cycloadditions of a boryl azide.[23] All these compounds are stable to chromatography and ambient laboratory conditions. In contrast, it has not yet been possible to make stable NHC–borylamines, for example. On the basis of these early trends, stable NHC–boranes with B–N bonds

dx.doi.org/10.1021/ja403627k | J. Am. Chem. Soc. 2013, 135, 10484–10491

should be designed with electron-poor rather than electron-rich nitrogen atoms.

In other classes of boron chemistry, many anionic azolyl borate complexes are known. Within this class, complexes such as **19** can be viewed as neutral analogues of the anionic mercaptoazolyl borohydrides described by Santos and co-workers, where one hydride is replaced by NHC.[24] These complexes are made from acid/base reactions of sodium borohydride with weakly acidic N-heterocycles such as 2-mercapto-1-methylimidazole.

A similar reaction of **1** now with 2 equiv of disulfide **17** was conducted for about 1 h, at which time starting NHC−borane **1** was consumed. This reaction gave three separable products in 83% combined isolated yield. The only monoadduct isolated was amide borane−NHC complex **19** (29%). Two disubstituted adducts, **20** and **21**, were isolated in 39% and 15% yields. The resonances of the heteroaryl carbons in the ^{13}C NMR spectrum of the major product **20** all came in pairs. For example, C2/C2′ resonated at 171 and 193 ppm. This implies that **20** is a chiral complex (boron is a stereocenter) with one B−N bond (C2′ at 193 ppm) and one B−S bond (C2 at 171 ppm). The corresponding heteroaryl resonances in the minor product **21** were not paired but instead were doubled in intensity. The key C2 nucleus resonated at 171 ppm; therefore, this is the symmetrical boryl disulfide **21**.

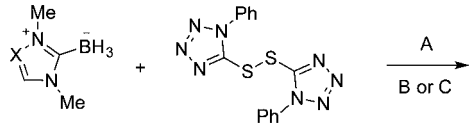
We next conducted several experiments to better understand the timing of the substitution and the rearrangement. Prolonged irradiation or heating of symmetric diadduct **21** did not produce **20**. Instead, only gradual decomposition was observed. In contrast, reaction of the monoadduct **19** with more disulfide **17** indeed gave the unsymmetrical product **20**. This suggests that when 2 equiv of disulfide **17** is reacted with **1**, the primary adduct **18** rearranges to **19** in competition with a second sulfanylation to give **21**. The symmetric adduct **21** does not rearrange easily to **20**; instead, this forms by sulfanylation of already rearranged **19**.

To test the scope of the rearrangement of the boron from sulfur to nitrogen, we investigated the reactions with 5,5′-dithiobis(1-phenyl-1*H*-tetrazole) **22** (commonly called bis(1-phenyltetrazolyl) disulfide, PTSSPT) with different NHC−boranes (**1**, **8**, and **14**) under dark (A) and light conditions (B and C). These results are summarized in Scheme 2. DiMe-Imd−BH_3 **1** and diMe-Triaz−BH_3 **14** behaved similarly. Under thermal conditions (A, 1 equiv of **22**), the rearranged monoadducts **23** and **24** were isolated in 85% and 81% yields. Again these products were stable, and the ^{13}C NMR spectrum evidenced the rearrangement (C2 at 167 ppm in both products). Under light conditions (B or C with 2 equiv of **22**), the asymmetrical disubstituted complexes **25** (C2 at 167 and C2′ at 156 ppm) and **26** (similar values) were isolated in 75% and 65% yields. Clearly the first S-to-N shift is relatively fast in this series.[26]

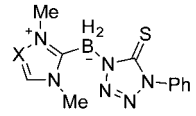
Interestingly, the reactions of dipp-Imd−BH_3 **8** took the reverse course. Under conditions A, the unrearranged monosulfide **27** was isolated in 55% yield (C2 at 159 ppm), while conditions B gave the symmetrical boryl disulfide **28** in 44% yield (C2 at 156 ppm). So far we have not been able to induce either **27** or **28** to rearrange to an isomer with a B−N bond. These early results show the importance of the size of the N substituent on the 1,3-boryl shift; small groups (Me) allow it and large ones (dipp) do not. Calculations of ΔH° for **23** in the Supporting Information suggest that the B−N bonds of the rearranged products are as much as 10 kcal mol^{-1} stronger than

Scheme 2. Products and Isolated Yields in Reaction with Phenyltetrazolyl Disulfide: (a) Rearranged Products with Smaller Boranes; (b) Unrearranged Products with Bulky Boranes[a]

*(a) Reaction of **22** with smaller NHC-boranes **1** and **14***

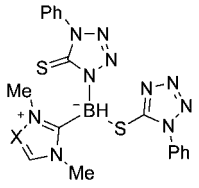


from dark conditions



23, X = CH, 85%, 2 h[a]
24, X = N, 81%, 2 h[a]

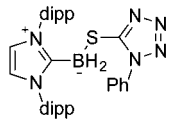
from light conditions



25, X = CH, 75%, 4 h[b]
26, X = N, 65%, 0.5 h[c]

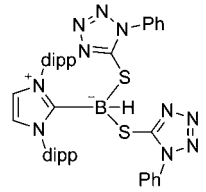
*(b) Products from reactions of **22** with bulky NHC-borane **8***

from dark conditions



27, 55%, 4 h[a]

from light conditions



28, 44%, 10 h[b]

[a]conditions A; [b]conditions B; [c]conditions C.

the starting B−S bonds. This in turn suggests that **27** resists rearrangement because of a kinetic barrier, not because it is more stable than its isomer.

Reaction Mechanism. We suggest that under conditions of irradiation, the products form by radical chains like those discovered in the LFP experiments, with the steps of hydrogen abstraction and homolytic substitution. These are shown in Figure 3, steps 1 and 2, for formation of the boryl sulfide product, and the boryl disulfide product is formed analogously. The initiating radical is presumably PhS· derived from disulfide homolysis. The light-promoted reactions are fast, and selective formation of the monosulfide product is not practical. However, they reliably stop at the disulfide, perhaps because the third substitution is less exothermic (see Figure 4).

Conducting reactions in the dark slows the rate significantly, and good yields of the monosulfide product can be obtained along with variable (but always lesser) amounts of the NHC−boryl disulfide. The yields of the dark reactions also seem more dependent on the structure of the starting NHC−borane, with smaller (and perhaps more nucleophilic[21]) NHCs giving better yields (see Table 2). Accordingly, dark reactions of disulfides might occur either by the radical chain or by an ionic mechanism like that shown in Figure 6. Here the NHC−borane behaves as a hydride donor that reduces the disulfide electrophile to a thiol.[25] By analogy, alkyl iodides have previously been observed to react by radical and hydridic

dx.doi.org/10.1021/ja403627k | J. Am. Chem. Soc. 2013, 135, 10484−10491

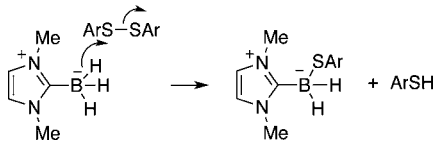


Figure 6. Possible ionic mechanism for formation of monosulfides. The NHC–borane behaves as a hydride donor.

(ionic) mechanisms with NHC–boranes, depending on the reaction conditions and the structure of the iodide.[27]

To help sort this out, we conducted dark reactions at 45 °C with **1** and diphenyl disulfide or bis(2-phenyltetrazolyl) disulfide **22** in the presence of 1 equiv of the radical trap 2,2,6,6-tetramethylpiperidin-1-yloxyl (commonly called TEMPO). With the less electrophilic diphenyl disulfide, no conversion at all occurred over 48 h. Contrast this to entry 5 in Table 1 (no TEMPO), where the starting NHC–borane was consumed in 6 h.

On the other hand, the reaction of **1** and the more electrophilic (2-phenyltetrazolyl) disulfide **22** with TEMPO present gave >90% conversion to rearranged **23** after 16 h. Still, complete conversion in a comparable experiment without TEMPO was observed after only 2 h (Scheme 2). Tentatively then, less electrophilic disulfides probably react primarily by radical chains even under dark conditions, while more electrophilic disulfides may react by either ionic or competing radical and ionic pathways.

The S-to-N rearrangement can occur by several pathways that are sketched in more detail in the Supporting Information. Briefly, this could be a direct 1,3-shift or a bimolecular reaction where one adduct behaves as an electrophile and the other as a nucleophile. At this early stage, a radical mechanism (boryl radical addition to N, then elimination from S) seems less likely because TEMPO did not suppress the rearrangement to **23** in the reaction of **22** (Scheme 2).

■ CONCLUSIONS

The presence of oxygen or isopropyl iodide during LFP experiments with NHC–boranes and disulfides caused a dramatic decrease in the apparent lifetime of the phenylthiyl radical. We deduced that this happens because the additives break a chain reaction whose steps are (1) hydrogen abstraction from NHC–BH_3 by a thiyl radical and (2) homolytic substitution of a disulfide by the resulting boryl radical. This second step is a new reaction. The additives break the chain by intercepting the boryl radical.

These experiments led to the discovery that NHC–boryl sulfides, a heretofore little known class of compounds,[28] are generally available from NHC–boranes and diaryl disulfides. Preparative substitution reactions of NHC–BH_3 and ArSSAr selectively gave stable disubstituted (NHC–$BH(SAr)_2$) products under light conditions, while the same substrates preferentially led to the monosubstituted (NHC–BH_2SAr) derivatives in the dark. Reactions under light occur by the homolytic substitution chain mechanism, but the dark reactions may occur by ionic mechanisms or inefficient chains, depending on the disulfide structure. When benzothiazolyl and phenyltetrazolyl disulfides were used, a new B–S to B–N rearrangement was observed, providing the first stable amidoborane-type NHC complexes (Scheme 1).

In short, we have expanded the chemistry of boryl radicals by identifying a new radical chain homolytic substitution reaction with disulfides. The reactions of NHC–boranes and disulfides are easy to conduct and provide robust boryl sulfides or boryl N-heterocycles that are stable to ambient laboratory conditions (air and water) and purification techniques (chromatography). They are therefore candidates as reagents in small-molecule or polymer chemistry and in main-group chemistry as precursors for other types of NHC–boranes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Text, tables, figures, and CIF files giving full details for scouting, preparative, and laser flash photolysis experiments, NMR spectra (^1H, ^{11}B, ^{13}C) of all new compounds, and crystallographic data for the crystal structures. This material is available free of charge via the Internet at http://pubs.acs.org/.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: curran@pitt.edu (D.P.C.); jacques.lalevee@uha.fr (J.L.); emmanuel.lacote@univ-lyon1.fr (E.L.).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the U.S. National Science Foundation, the French Agence Nationale de Recherche (grant ANR-11-BS07-008, NHCX), UHA, ENSCMu, and CNRS for funding this work. E.L. thanks Actelion and ENSCMu for the Actelion award.

■ REFERENCES

(1) (a) Davies, A. G.; Roberts, B. P. *Acc. Chem. Res.* **1972**, *5*, 387–392. (b) Davies, A. G. *Pure Appl. Chem.* **1974**, *39*, 497–503. (c) Brown, H. C.; Midland, M. M. *Angew. Chem., Int. Ed.* **1972**, *11*, 692–700.

(2) (a) Lalevée, J.; Fouassier, J. P. In *Encyclopedia of Radicals in Chemistry, Biology and Materials*; Chatgilialoglu, C., Studer, A., Eds.; Wiley: New York, 2012; Vol. *1*, pp 37–56. (b) Denisov, E. T.; Denisova, T. G.; Pokidova, T. S. In *Handbook of Free Radical Initiators*; Wiley: New York, 2003; pp 767–781. (c) Yorimitsu, H.; Oshima, K. In *Radicals in Organic Synthesis*; Renaud, P., Sibi, M. P., Eds.; Wiley-VCH: Weinheim, Germany, 2001; Vol. *1*, pp 11–27.

(3) (a) Renaud, P. In *Encyclopedia of Radicals in Chemistry, Biology and Materials*; Chatgilialoglu, C., Studer, A., Eds.; Wiley: New York, 2012; Vol. *1*, pp 601–628. (b) Renaud, P.; Beauseigneur, A.; Brecht-Forster, A.; Becattini, B.; Darmency, V.; Kandhasamy, S.; Montermini, F.; Ollivier, C.; Panchaud, P.; Pozzi, D.; Scanlan, E. M.; Schaffner, A. P.; Weber, V. *Pure Appl. Chem.* **2007**, *79*, 223–233. (c) Darmency, V.; Renaud, P. *Top. Curr. Chem.* **2006**, *263*, 71–106.

(4) (a) Haque, M. B.; Roberts, B. P.; Tocher, D. A. *J. Chem. Soc., Perkin Trans. 1* **1998**, 2881–2889. (b) Elford, P. E.; Roberts, B. P. *J. Chem. Soc., Perkin Trans. 2* **1998**, 1413–1422. (c) Dang, H. S.; Roberts, B. P. *J. Chem. Soc., Perkin Trans. 1* **1993**, *I*, 891–898. (d) Sheeller, B.; Ingold, K. U. *J. Chem. Soc., Perkin Trans. 2* **2001**, 480–486. (e) Roberts, B. P. *Chem. Soc. Rev.* **1999**, *28*, 25–35. (f) Staubitz, A.; Robertson, A. P. M.; Sloan, M. E.; Manners, I. *Chem. Rev.* **2010**, *110*, 4023–4078. (g) Barton, D. H. R.; Jacob, M. *Tetrahedron Lett.* **1998**, *39*, 1331–1334.

(5) (a) Giles, J. R. M.; Roberts, B. P. *J. Chem. Soc., Perkin Trans 2* **1983**, 743–755. (b) Kawamoto, T.; Fukuyama, T.; Ryu, I. *J. Am. Chem. Soc.* **2012**, *134*, 875–877. (c) Kinjo, R.; Donnadieu, B.; Celik, M. A.; Frenking, G.; Bertrand, G. *Science* **2011**, *333*, 610–613. (d) Braunschweig, H.; Dyakonov, V.; Jimenez-Halla, J. O. C.; Kraft, K.; Krummenacher, I.; Radacki, K.; Sperlich, A.; Wahler, J. *Angew. Chem., Int. Ed.* **2012**, *51*, 2977–2980.

(6) Kaim, W.; Hosmane, N. S.; Záliš, S.; Maguire, J. A.; Lipscomb, W. N. *Angew. Chem., Int. Ed.* **2009**, *48*, 5082−5091.
(7) *Encyclopedia of Radicals in Chemistry, Biology and Materials*; Chatgilialoglu, C., Studer, A., Eds.; Wiley: New York, 2012; Vols. *1*−*4*.
(8) (a) Li, C. In *Encyclopedia of Radicals in Chemistry, Biology and Materials*; Chatgilialoglu, C., Studer, A., Eds.; Wiley: New York, 2012; Vol. *1*, pp 943−964. (b) Schiesser, C. H. *Chem. Commun.* **2006**, 4055−4065. (c) Crich, D. *Helv. Chim. Acta* **2006**, *89*, 2167−2182.
(9) (a) Ueng, S.-H.; Makhlouf Brahmi, M.; Derat, É.; Fensterbank, L.; Lacôte, E.; Malacria, M.; Curran, D. P. *J. Am. Chem. Soc.* **2008**, *130*, 10082−10083. (b) Ueng, S.-H.; Solovyev, A.; Yuan, X.; Geib, S. J.; Fensterbank, L.; Lacôte, E.; Malacria, M.; Newcomb, M.; Walton, J. C.; Curran, D. P. *J. Am. Chem. Soc.* **2009**, *131*, 11256−11262. (c) Walton, J. C.; Makhlouf Brahmi, M.; Fensterbank, L.; Lacôte, E.; Malacria, M.; Chu, Q.; Ueng, S.-H.; Solovyev, A.; Curran, D. P. *J. Am. Chem. Soc.* **2010**, *132*, 2350−2358. (d) Walton, J. C.; Brahmi, M. M.; Monot, J.; Fensterbank, L.; Malacria, M.; Curran, D. P.; Lacôte, E. *J. Am. Chem. Soc.* **2011**, *133*, 10312−10321.
(10) Curran, D. P.; Solovyev, A.; Makhlouf Brahmi, M.; Fensterbank, L.; Malacria, M.; Lacôte, E. *Angew. Chem., Int. Ed.* **2011**, *50*, 10294−10317.
(11) Hioe, J.; Karton, A.; Martin, J. M. L.; Zipse, H. *Chem. Eur. J.* **2010**, *16*, 6861−6865.
(12) (a) Tehfe, M.-A.; Monot, J.; Malacria, M.; Fensterbank, L.; Fouassier, J.-P.; Curran, D. P.; Lacôte, E.; Lalevée, J. *ACS Macro Lett.* **2012**, *1*, 92−95. (b) Lalevée, J.; Telitel, S.; Tehfe, M. A.; Fouassier, J. P.; Curran, D. P.; Lacôte, E. *Angew. Chem., Int. Ed.* **2012**, *51*, 5958−5961. (c) Tehfe, M.-A.; Monot, J.; Makhlouf Brahmi, M.; Bonin-Dubarle, H.; Curran, D. P.; Malacria, M.; Fensterbank, L.; Lacôte, E.; Lalevée, J.; Fouassier, J.-P. *Polym. Chem.* **2011**, *2*, 625−631. (d) Tehfe, M.-A.; Makhlouf Brahmi, M.; Fouassier, J.-P.; Curran, D. P.; Malacria, M.; Fensterbank, L.; Lacôte, E.; Lalevée, J. *Macromolecules* **2010**, *43*, 2261−2267. (e) Telitel, S.; Schweizer, S.; Morlet-Savary, F.; Graff, B.; Tschamber, T.; Blanchard, N.; Fouassier, J. P.; Lelli, M.; Lacôte, E.; Lalevée, J. *Macromolecules* **2012**, *46*, 43−48.
(13) Ueng, S.-H.; Fensterbank, L.; Lacôte, E.; Malacria, M.; Curran, D. P. *Org. Lett.* **2010**, *12*, 3002−3005.
(14) Pan, X.; Lacôte, E.; Lalevée, J.; Curran, D. P. *J. Am. Chem. Soc.* **2012**, *134*, 5669−5675.
(15) Matsumoto, T.; Gabbaï, F. P. *Organometallics* **2009**, *28*, 4252−4253.
(16) (a) Monot, J.; Solovyev, A.; Bonin-Dubarle, H.; Derat, É.; Curran, D. P.; Robert, M.; Fensterbank, L.; Malacria, M.; Lacôte, E. *Angew. Chem., Int. Ed.* **2010**, *49*, 9166−9169. (b) Bissinger, P.; Braunschweig, H.; Kraft, K.; Kupfer, T. *Angew. Chem., Int. Ed.* **2011**, *50*, 4704−4707. (c) Curran, D. P.; Boussonnière, A.; Geib, S. J.; Lacôte, E. *Angew. Chem., Int. Ed.* **2012**, *51*, 1602−1605.
(17) Yeh, E. A.; Kumli, E.; Damodaran, K.; Curran, D. P. *J. Am. Chem. Soc.* **2013**, *135*, 1577−1584.
(18) Lacôte, E.; Curran, D. P.; Lalevée, J. *Chimia* **2012**, *66*, 382−385.
(19) Borges dos Santos, R. M.; Muralha, V. n. S. F.; Correia, C. F.; Guedes, R. C.; Costa Cabral, B. J.; Martinho Simões, J. A. *J. Phys. Chem. A* **2002**, *106*, 9883−9889.
(20) Solovyev, A.; Chu, Q.; Geib, S. J.; Fensterbank, L.; Malacria, M.; Lacôte, E.; Curran, D. P. *J. Am. Chem. Soc.* **2010**, *132*, 15072−15080.
(21) Nagura, K.; Saito, S.; Frohlich, R.; Glorius, F.; Yamaguchi, S. *Angew. Chem., Int. Ed.* **2012**, *51*, 7762−7766.
(22) (a) Ogawa, A.; Curran, D. P. *J. Org. Chem.* **1997**, *62*, 450−451. (b) Maul, J. J.; Ostrowski, P. J.; Ublacker, G. A.; Linclau, B.; Curran, D. P. In *Modern Solvents in Organic Synthesis*; Knochel, P., Ed.; Springer-Verlag: Berlin, 1999; Topics in Current Chemistry *206*, pp 80−104. (c) Matsubara, H.; Ryu, I. *Top. Curr. Chem.* **2012**, *308*, 135−152.
(23) Merling, E.; Lamm, V.; Geib, S. J.; Lacôte, E.; Curran, D. P. *Org. Lett.* **2012**, *14*, 2690−2693.
(24) Maria, L.; Paulo, A.; Santos, I. C.; Santos, I.; Kurz, P.; Spingler, B.; Alberto, R. *J. Am. Chem. Soc.* **2006**, *128*, 14590−14598.
(25) Horn, M.; Mayr, H.; Lacôte, E.; Merling, E.; Deaner, J.; Wells, S.; McFadden, T.; Curran, D. P. *Org. Lett.* **2012**, *14*, 82−85.
(26) No symmetrical boryl disulfide was isolated in the photochemical experiment with **1** and **22**. However, the reaction of **14** and **22** provided 6% of this product, Me-triaz-BH(Sbenzothiazolyl)$_2$. Its data are provided in the Supporting Information.
(27) Chu, Q.; Makhlouf Brahmi, M.; Solovyev, A.; Ueng, S.-H.; Curran, D.; Malacria, M.; Fensterbank, L.; Lacôte, E. *Chem. Eur. J.* **2009**, *15*, 12937−12940.
(28) For ligated amine−boryl sulfides, see: (a) Davis, B. L.; Dixon, D. A.; Garner, E. B.; Gordon, J. C.; Matus, M. H.; Scott, B.; Stephens, F. H. *Angew. Chem., Int. Ed.* **2009**, *48*, 6812−6816. (b) Robertson, A. P. M.; Haddow, M. F.; Manners, I. *Inorg. Chem.* **2012**, *51*, 8254−8264.