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New insight into the mechanism of the reaction between α,β-unsaturated carbonyl compounds and triethylborane (Brown's reaction)

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Abstract

A study of the reaction of α,β-unsaturated carbonyl compounds with triethylborane under free radical conditions (Brown's reaction) including spectroscopic analyses (^{11}B NMR, IR, EPR) of products and intermediates indicated that these reactions involve the prior formation of an 'α,β-unsaturated carbonyl compound–organoborane' complex.

Keywords: boron and compounds; complexation; carbonyl compounds; enones; radicals and radical reactions.

Organoboranes are known to undergo exceptionally fast 1,4-addition to many α,β-unsaturated carbonyl compounds such as methyl vinyl ketone (MVK)[1,2] and acrolein.[2,3] Subsequent addition of water to the reaction mixture results in rapid hydrolysis of the intermediate vinyloxyborane (**1**), with liberation of the corresponding aldehyde or ketone (**2**) (Scheme 1). Brown and Kabalka suggested that this addition occurs via a free radical chain mechanism.[4] Recently, Bieber and co-workers reported that alkylation of 2-methoxy-1,4-quinone, via free radical reaction with trialkylboranes, occurred regioselectively in the 5-position.[5] They invoked the existence of a quinone–borane complex to explain this result. More recently, Malacria and co-workers demonstrated the efficiency of triethylborane mediated free radical cyclizations onto the carbonyl of a ketone.[6] They also suggested the formation of a complex between the borane and the ketone to account for the high reactivity of C=O and the observed chemoselectivity in the cyclization of enal precursors. These recent papers and the review of Renaud and Gerster[7] on the use of Lewis acids in free radical chemistry prompted us to present our results on Brown's reaction, including

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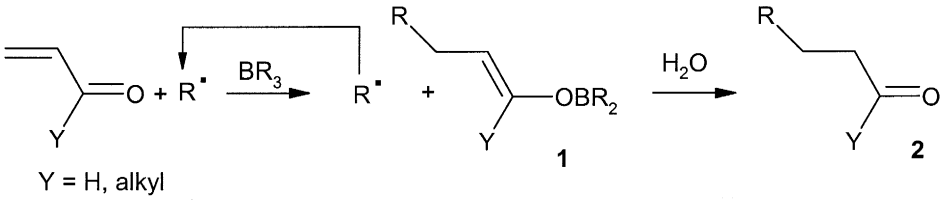
our spectroscopic observations of the complexes formed between α,β-unsaturated carbonyl compounds and triethylborane.



Scheme 1. Free-radical alkylation of enones (Brown's reaction)

In connection with the possible free radical homopolymerization of MVK,[8] the fact that Brown did not detect the presence of any oligomer in the reaction medium is surprising. However, we confirmed that when freshly distilled MVK[9] was stirred for 1 h in dry benzene, at 60°C, under an argon atmosphere, in the presence of catalytic amounts of AIBN (0.2 mol% of the ketone), a poly(MVK) sample of 104 000 g. mol^{-1} molar mass was isolated. By contrast, when the same reaction was performed in the presence of one equivalent of triethylborane,[10] with respect to MVK, the conditions being otherwise similar, the only product formed was hexan-2-one (84%). No polymer or oligomer could be detected by GC after evaporation of the solvent. Brown's explanation for this singular result was that the intermediate MVK adduct-radical would be oxygen centred and hence would react very rapidly with triethylborane.

Applying this hypothesis in connection with the analogous fast addition of alkoxyl radicals to phosphorous compounds (e.g. the rate constant for *t*-butoxyl radical addition to triethylphosphite is ca. 2×10^9 M^{-1} s^{-1})[11] implies that the AIBN initiated reaction of MVK with $P(OEt)_3$ should give some hexan-2-one. However, irrespective of the conditions used, only poly(MVK) was isolated after removal of the solvent. This lack of reactivity of the growing polymeric radicals with phosphite seems to indicate that the specific reactivity of radicals arising from the MVK/BEt_3 reaction cannot be merely attributed to a high electron density on the carbonyl oxygen atom of the propagating species.

Boron has a high affinity for oxygen, as evidenced by the B–O bond dissociation energy in several molecules (808.8 kJ mol^{-1})[12] and hence has a penchant to react with a variety of Lewis bases forming corresponding complexes.[13] It occurred to us therefore that Brown's reaction might involve a transient 'carbonyl compound–BR_3' complex. After confirming by ^1H NMR that no addition reaction occurred when MVK and BEt_3 were mixed, the formation of a complex was demonstrated by ^{11}B NMR. Recorded in oxygen free conditions[14] the ^{11}B NMR spectrum indicated that the chemical shift of the boron atom in BEt_3 was significantly affected by the presence of MVK (Table 1, entries 1 and 2). Indeed, the single peak due to the boron atom now appeared at −53.39 ppm as against −86.45 ppm in the absence of ketone (relative to BF_3 etherate). Likewise, IR spectra of MVK–triethylborane equimolar mixtures, performed in oxygen free conditions[15] showed that the $\nu_{C=O}$ band of the ketone was shifted to higher frequency by the presence of BEt_3 (Table 1).

We also examined whether this complexation is a general phenomenon or is peculiar to MVK. Acrolein[2,3] and 3-methylbut-3-en-2-one[16] were also successfully used in the Brown reaction, so their equimolar mixtures with triethylborane were analysed by IR and ^{11}B NMR. In each case, the $\nu_{C=O}$ band was found to be shifted by the presence of BEt_3 (Table 1, entries 3 and 4) and the ^{11}B chemical shifts were in agreement with complex formation (Table 1, entries 1, 3 and 4).

The question that then arose was whether MVK formed similar complexes with alkylborinates. In fact, Et_2BOMe failed to participate in the AIBN-induced free radical reaction with MVK and only poly(MVK) (M_n of about 2090) was ultimately obtained. Since the chemical shift of the boron atom in the 'BEt_3–MVK' complex is of the same order of magnitude as that observed for alkylborinates, the

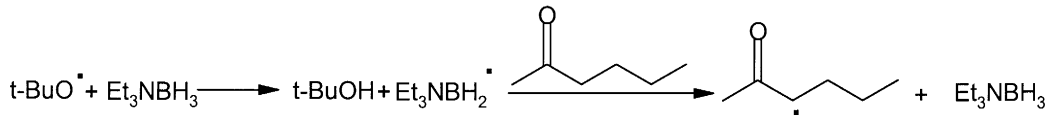
Table 1
^{11}B NMR and IR data for carbonyl compound–organoborane equimolar mixtures

Entry	Boron compound	Carbonyl compound	^{11}B chemical shift (ppm)	$\nu_{C=O}/cm^{-1}$ without BEt_3	$\nu_{C=O}/cm^{-1}$ with BEt_3
1	BEt_3	-	-86.45	-	-
2	BEt_3	MVK	-53.39	1687-1707[a]	1688-1721
3	BEt_3	Acrolein	-53.86	1702	1729
4	BEt_3	3-Methylbut-3-en-2-one	-53.31	1683	1716
5	Et_2BOMe	-	-53.91	-	-
6	Et_2BOMe	MVK	-53.86	-	-

[a] Range due to the presence of *S-cis* and *S-trans* isomers

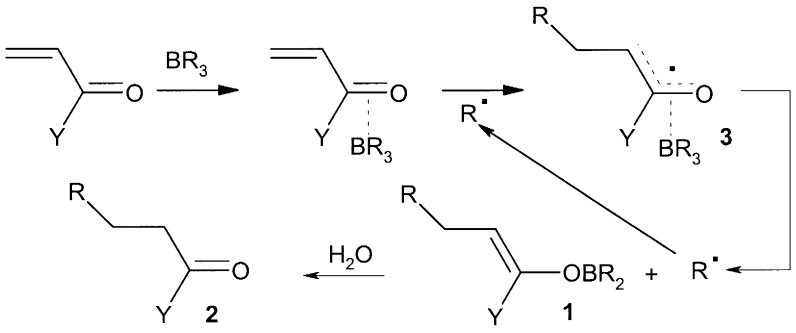
presumed ^{11}B chemical shift for a 'Et_2BOMe–MVK' complex should appear around −30 ppm, which is the chemical shift observed for a two oxygen bonded boron atom.[17] It turns out that the ^{11}B NMR of an equimolar mixture of this alkylborinate and MVK exhibits a single peak at −53.86 ppm (Table 1, entry 6), indicating that Et_2BOMe and MVK do not form any complex when mixed together.

The mechanism implied that the complexed propagating radical **3** underwent a dissociative rearrangement to afford vinyloxyborane and release an alkyl radical, in preference to intermolecular addition to another enone molecule (Scheme 2). Evidence for the existence of complexed radicals was sought by examining the 9 GHz EPR spectra obtained on photolysis of a solution of BEt_3 and MVK in di-*t*-butyl peroxide. *t*-Butoxyl radicals produced by photolysis were expected to displace ethyl radicals from BEt_3. These ethyl radicals should then add to MVK to produce complexed adduct radicals **3** (Y=Me). The EPR spectrum at 270 K displayed a quartet structure with a(3H)=18.4 G which corresponds to radical **3** (Y=Me) with the α-H and two β-H having coincidentally equal hyperfine splitting (hfs). For comparison the uncomplexed adduct radical was generated by hydrogen abstraction from hexan-2-one also using *t*-BuO· radicals. In this case the *t*-BuO· radicals abstracted unselectively and the spectrum consisted of at least two radicals one having a quartet structure [a(3H)=19.2 G] which we attribute to the uncomplexed adduct radical (hexan-2-one-3-yl) and another having a double quintet corresponding to the hexan-2-one-5-yl radical. To confirm our identification of the uncomplexed hexan-2-one-3-yl radical we used Roberts' polarity reversal catalysis method (with Et_3NBH_3) to selectively abstract hydrogen adjacent to the carbonyl group:[18]



Photolysis of hexan-2-one and *t*-BuOOBu-*t* with added amine–borane furnished solely the quartet EPR spectrum of hexan-2-one-3-yl with a(3H)=19.3 G at 270 K. The significantly smaller hfs of the radical in the presence of BEt_3 is entirely consistent with complexation which results in measurable withdrawal of spin density from the enone moiety.

In conclusion, it appears that Brown's reaction indeed occurs via an 'α,β-carbonyl compound–organoborane' complex. Considering that MVK easily copolymerizes with several monomers, it appears to be of great interest to take advantage of the 'MVK–BEt_3' complex as a chain transfer agent in free radical polymerizations. This possibility is currently under active investigation in our laboratories.



Scheme 2. Mechanism of alkylation via complexed enones

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