Radical Rearrangements of Bicyclo[2.2.0]hexane: Homolytic Substitution of a Cyclobutane Ring

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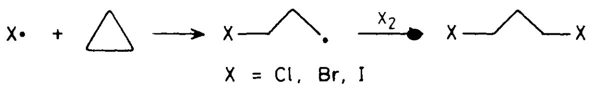
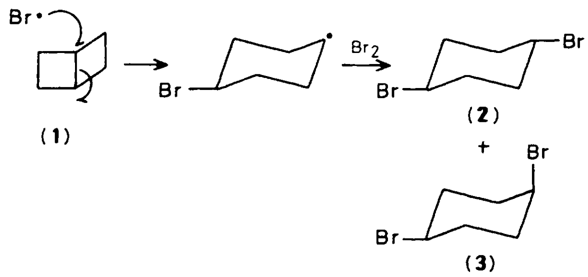
Bromine atoms react with bicyclo[2.2.0]hexane in an S_H2 reaction at the bridgehead carbon atoms; the bicyclo[2.2.0]hex-2-yl radical rearranges by β-scission of the inter-ring bond.

Bimolecular homolytic substitution (S_H2) at saturated carbon atoms is rare[1] although at least one example is known.[2] The main exception to this rule is found with highly strained cyclopropanes which undergo rapid substitution by halogen atoms, equation (1),[3] and the pseudo-halogen bis(trifluoromethyl)aminoxyl.[4]

This reaction, with suitably substituted cyclopropanes, has been utilised to show that homolytic displacement on carbon



(1)



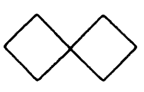
involves inversion of configuration.[5—8] The ring strain of cyclobutane (110 kJ mol^{-1}) is only slightly less than that of cyclopropane (115 kJ mol^{-1})[9] but chlorination[10] and bromination[11] of cyclobutane and its derivatives[12—14] occurs by straightforward hydrogen abstraction. An $S_{\mathrm{H}}2$ reaction has not previously been observed for a cyclobutane ring, except in the fluorination of perfluorocyclobutane which involves vibrationally excited species.[15] We have found, however, that bicyclo[2.2.0]hexane, (**1**), which contains two fused cyclobutane rings, does undergo homolytic substitution at the bridgehead carbon atoms.

The photobromination of *cis*-bicyclo[2.2.0]hexane, (**1**), in CCl$_4$ solution at ambient temperature was rapid, being complete in less than 30 min, and 'clean' giving two main products, *trans*-1,4-dibromocyclohexane, (**2**) (57%), and *cis*-1,4-dibromocyclohexane, (**3**) (40%) together with a minor amount of *trans*-1,2-dibromocyclohexane (2%).† Monobromides amounted to less than 1% of the total products. The very specific formation of 1,4-dibromocyclohexanes points to an $S_{\mathrm{H}}2$ attack by bromine atoms at the bridgehead carbon atoms as the first step in the reaction.

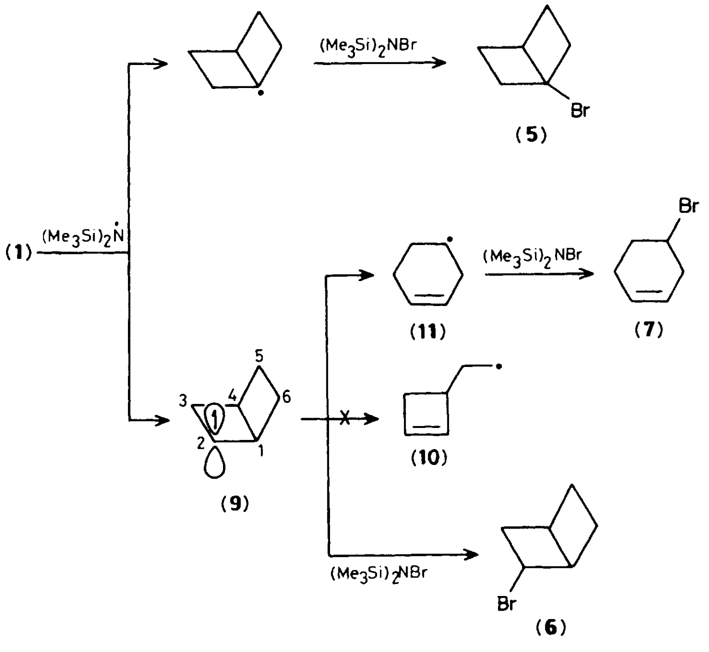
Several alternative routes to the dibromides involving monobromination of (**1**) as the first step, followed by a second bromination stage, can be envisaged but, the almost complete absence of monobromides and 1,3-dibromides amongst the products militates heavily against these possibilities. We attribute the small amount of *trans*-1,2-dibromocyclohexane to a minor electrophilic bromination similar to that observed with cyclopropanes.[8]

The fact that the (**2**) : (**3**) ratio of 1.4 : 1 obtained from (**1**) was similar to the (**2**) : (**3**) ratio of 1.1 : 1 reported for the photobromination of bromocyclohexane[16] supports the proposed mechanism because the final step in both reactions is identical. The chlorination of (**1**) led to a complex mixture containing monochlorides and many unidentified dichlorides.[17] Thus the main hydrogen abstraction reactions in the photochlorination may be accompanied by an $S_{\mathrm{H}}2$ process involving chlorine atoms.

The ring strain in (**1**) is high[18] at 217 kJ mol^{-1}, but it is not this factor alone which leads to this unusual $S_{\mathrm{H}}2$ reaction. Bromination of spiro[3.3]heptane, (**4**), with a strain energy of *ca.* 220 kJ mol^{-1}, takes place exclusively by hydrogen abstraction and no $S_{\mathrm{H}}2$ process was observed.[19] The C-1–C-4 bond in (**1**) is unusually long (an electron diffraction study gives 1.577 Å).[20] Recent theoretical calculations have indicated that this bond is bent and contains significantly less s-character than the C–C bonds of cyclobutane.[18,21,22] We expect that this $S_{\mathrm{H}}2$ reaction will be general for the halogenation of molecules containing fused cyclobutane rings.


(**4**)


(**8**)



Scheme 1

Attempts to identify the radicals formed by hydrogen abstraction from (**1**) by t-butoxyl radicals, using e.s.r. spectroscopy were unsuccessful. When (**1**) was allowed to react with bis(trimethylsilyl)-*N*-bromoamine under radical conditions[23] at 75 °C, a very slow process (*ca.* 50% reactant consumption in 62 h) yielded a mixture containing *ca.* 75% of monobromides, *i.e.* hydrogen abstraction was the predominant primary process. The monobromides were found to be: 1-bromobicyclo[2.2.0]hexane, (**5**) (34%), *exo*-2-bromobicyclo[2.2.0]hexane, (**6**) (35%), 4-bromocyclohexene, (**7**) (4%), and bromobenzene (2%). No other monobromides were detectable, but the same dibromides (total 16%) as in the photobromination were observed, together with minor unidentified products. Compounds (**5**)—(**7**) are analogous to the monochlorides obtained in the photochlorination of (**1**).[17] The formation of significant amounts of (**5**) shows that (**1**) joins bicyclo[1.1.1]pentane, (**8**), as another rare example of a hydrocarbon for which bridgehead hydrogen abstraction competes successfully with abstraction from the methylene hydrogens.[24,25] The comparatively slow reaction indicates that the preference for bridgehead attack in these two bicycloalkanes is probably due to deactivation of the bridge methylene groups rather than any enhanced bridgehead reactivity. This agrees with a recent theoretical analysis.[22]

The bicyclo[2.2.0]hexan-2-yl radical, (**9**), provides an interesting test of the current understanding of homolytic ring fission. β-Scission normally occurs readily if the SOMO can assume an eclipsed conformation with respect to the β—γ bond.[26] The rearrangement of (**9**) by scission of the C-1–C-6 bond to the cyclobutenylethyl radical, (**10**), is stereoelectronically allowed. On the other hand, rearrangement of (**9**) to the

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† Yields as mol% total products.

cyclohex-3-enyl radical, (**11**), is stereoelectronically forbidden because the C-1–C-4 bond is in the nodal plane of the SOMO (Scheme 1).

The presence of (**7**) and absence of products derived from radical (**10**), in both this and the photochlorination, shows that (**9**) rearranges mainly by the stereoelectronically forbidden route. The low yield of (**7**) indicates that rearrangement of (**9**) does not compete effectively with bromine abstraction to give (**6**). The unusual rearrangement mode is favoured because scission of the C-1–C-4 bond leads to relief of virtually all the strain in (**9**), whereas in the C-1–C-6 bond scission the cyclobutene ring strain remains in (**10**). The preference of radical (**9**) for the stereoelectronically forbidden rearrangement provides an apt illustration of the chemical consequences of the bending[18] in the inter-ring bond.

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