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Free radical addition of cyclopentane and cyclohexane to halogeno derivatives of 1,2-difluoroethene

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Abstract

Free radical addition reactions between cyclopentane and cyclohexane and a range of difluoroalkenes, CF_2=CXY (X, Y = H, F, Cl, Br) gave a series of adducts bearing difluoromethylene substituents, R-CF_2-CXYH (R = *c*-C_5H_9 or *c*-C_6H_{11}), in reasonable yield even though telomerisation and halogen transfer (when X, Y = Cl, Br) can compete. Dehydrofluorination of the adducts gave several new polyhalogenated alkenes.

1. Introduction

The incorporation of fluorine atoms into organic systems is becoming increasingly important due to the enhanced chemical and biological activity that selectively fluorinated systems can have over their non-fluorinated analogues [1]. The commercial availability of many life-science products that owe their bio-activity to the presence of fluorinated substituents exemplify these facts [2]. The introduction of difluoromethylene units into organic molecules is a particular target because of the ability of this moiety to act as an ether oxygen mimic [1] and several reagents have been developed for this purpose. In this context, diethylaminosulfur trifluoride (DAST) is widely used for the selective transformation of carbonyl groups into difluoromethylene groups [3] and numerous difluoromethylated natural product analogues have been synthesised [1].

An alternative strategy to the use of fluorinating agents for introducing fluorine into a target molecule is a 'building block' approach involving the synthetic manipulation of small molecules that already bear fluorinated groups into more elaborate systems [4]. This approach is, potentially, very synthetically versatile providing, of course, that a range of readily accessible and economically viable functional fluorine containing building blocks becomes available.

The carbon–hydrogen bond can be used as a functional group (C–H bond activation) in reactions between carbon-centred free radicals, derived from carbon–hydrogen bond homolysis by either γ-ray or peroxide initiation, and fluorinated alkenes. Free radical addition processes involving reactions of radicals generated from a variety of alkanes, [5] alcohols [6] and ethers [7–9] with fluoroalkenes have been established and, since these processes do not require the use of highly toxic organo-tin initiators, scale-up is a realistic possibility. Many fluorinated building blocks have been accessed by this free radical methodology and some subsequent chemistry of the free radical adducts has been explored [10–12]. Largely, however, studies have been concentrated on reactions involving hexafluoropropene (HFP) principally because HFP does not homopolymerise under normal reaction conditions and additions occur regioselectively at the difluoromethylene group (Scheme 1) allowing high yields of adducts to be formed.

Here, we describe our initial studies concerning reactions of radicals generated from cyclic alkanes with a variety of difluoroethylene derivatives in order to assess whether free radical addition methodology could be adapted to the ready synthesis of numerous fluorine-containing building blocks.

Of course, much related work concerning the synthesis of high molecular weight telomers from reactions between various difluoroalkenes (especially, CF_2=CH_2 and CF_2=CFCl) and a variety of telogens (alcohols, haloalkanes, etc.) has been published and this area of research has been reviewed recently [13]. Free radical addition reactions between carbon-centred radicals generated from, e.g. alcohols [14–17] aldehydes [18] and ethers [10,11,19,20] and some difluoroalkenes giving 1:1 adducts have also been described. However, we are unaware of any reports detailing reactions between radicals generated from hydrocarbons and difluoroalkenes.

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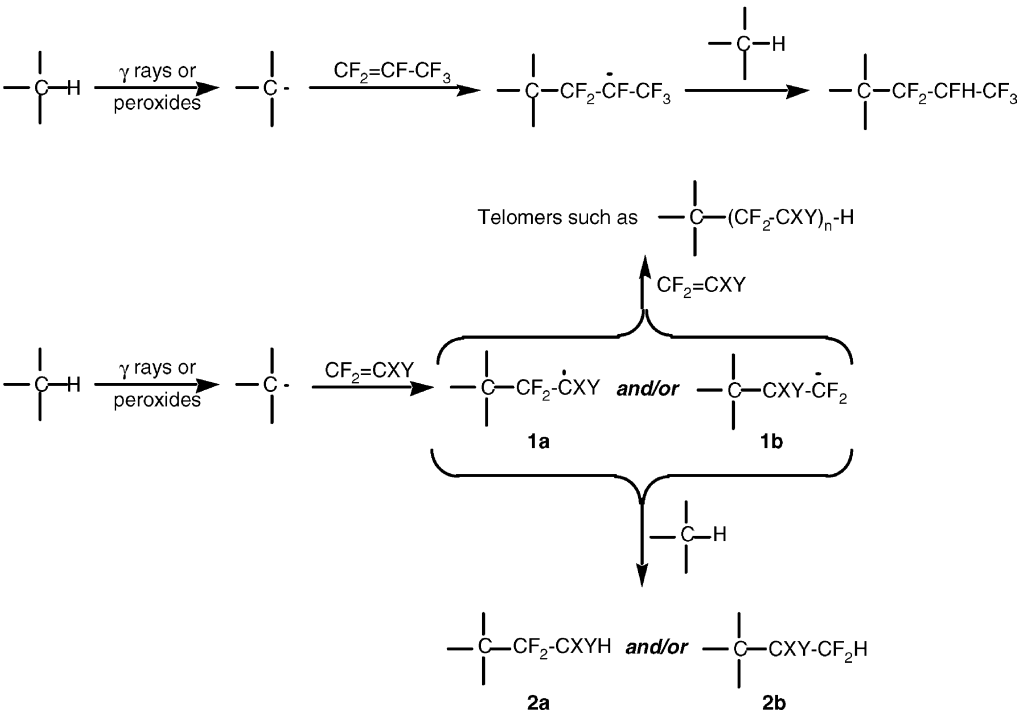


Scheme 1.

Addition of free radicals to CF_2=CXY systems could, in principle, give two intermediate radicals **1a** and **1b** (Scheme 1) which could then either abstract a hydrogen atom from the alkane starting material giving the desired adducts **2a** and **2b** or react with a further difluoroethylene molecule to give higher molecular weight material (telomers) (Scheme 1). The viability of this strategy, therefore, depends on the regioselectivity of the addition step and successfully limiting competing telomerisation processes.

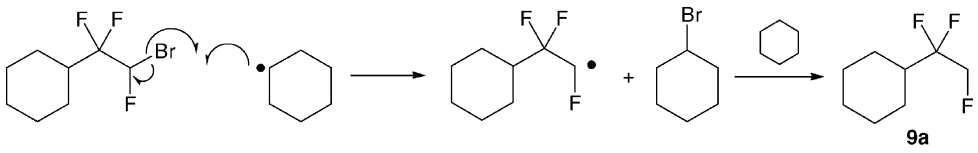
2. Results and discussion

Successful additions of free radicals generated from cyclopentane and cyclohexane, to various difluoroethylene derivatives were achieved, by either γ-ray or di-*tert*-butyl peroxide initiation at room temperature or 140 °C, respectively and the results are collated in Table 1. Structures of products were determined simply by NMR studies.

Reaction of cyclohexane with 1,1-difluoroethene (ratio alkane:alkene, 1:1) gave only intractable high molecular weight telomers and, even when a large excess of cyclohexane was used in an attempt to increase hydrogen transfer and minimise telomer formation, only a very low yield (8%) of a mixture of two monoaddition products **3** and **4** could be isolated.

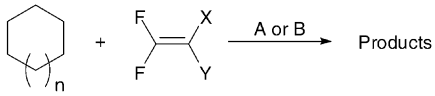
Trifluorochloroethene reacted with cyclohexane, present in large excess to minimise competing telomer formation, to give preparatively useful quantities of monoadduct **5** and a small amount of product **6**, arising from radical attack at the CFCl site. Trifluorobromo- and 1,1-difluoro-2-bromoethene also gave reasonable yields of monoadducts **7** and **9**, respectively in reactions with cyclohexane. In each case, the monoadduct products were accompanied by significant quantities of bromocyclohexane **8**, probably resulting from bromine atom abstraction by a cyclohexyl radical from adduct **7** (Scheme 2). Indeed, a small quantity of volatile trifluoroderivative **9a** was observed by GC/MS in support of this mechanism.

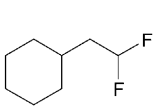
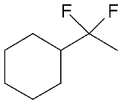
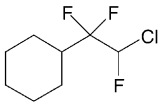
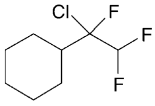
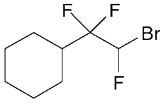
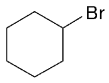
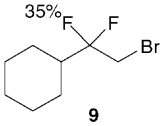
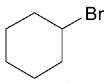
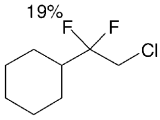
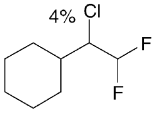
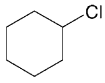
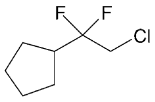
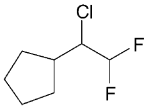
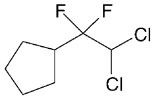
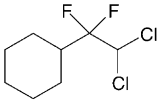
Difluoromethylene derivatives **10** and **14**, prepared in good yield by reaction of cyclohexane and cyclopentane with chlorodifluoroethene, respectively were also accompanied by a small quantity of products arising from radical attack at the CHCl site **11** and **15**, chlorocycloalkanes **12** and



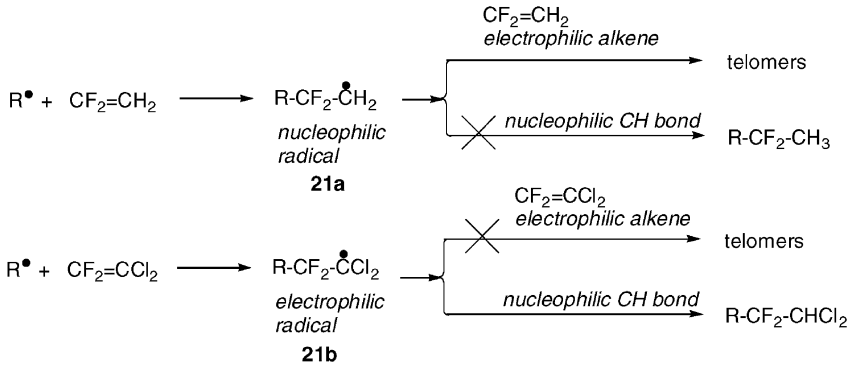
Scheme 2.

Table 1
Free radical additions to difluoroalkenes



Fluoroalkene (CF_2=CXY)	Conditions (A or B)[a]	Ratio (RH:alkane)	Products yield (%)
CF_2=CH_2	B	10:1	 **3**, 6%  **4**, 2% + telomers 74%
CF_2=CFCl	B	10:1	 **5**, 33%  **6**, trace + telomers 52%
CF_2=CFBr	A	2:1	 **7** 22%  **8** 44%
	B	4:1	35%  **9** 36%  **8** 23% 9%
CF_2=CHBr	A	4.4:1	19%  **10**, 49% 4%  **11**, 4%
	B	17:1	 **12**, 1% diadducts **13**, 5%
CF_2=CHCl	B	5:1	 **14**, 24%  **15**, trace diadducts **16**, 2%
CF_2=CCl_2	B	4:1	 **17**, 48% diadducts **18**, 4%
CF_2=CCl_2	A	1.5:1	 **19** 24% diadducts **20** 24%
	B	2.5:1	40% 3%

[a] Conditions: A, γ-ray irradiation, room temperature; B, *t*-BuO_2, 140 °C, 24 h.



Scheme 3.

16 (halogen abstraction analogous to that depicted in Scheme 2) and various diadducts. In contrast, additions of cyclopentane and cyclohexane to CF_2=CCl_2 gave difluorodichloro adducts **17** and **19**, respectively and only minor impurities.

Several aspects concerning the mechanism of the free radical reactions [21] described earlier are of note. The preferred sites for radical attack are the CF_2 groups and these positions are favoured because they are not only the most electrophilic sites due to the fluorine substituents, but are also the least sterically hindered site bearing only small fluorine atoms rather than larger chlorine and bromine substituents. These results are consistent with work involving free radical additions to various halogenated fluoropropene derivatives reported by Paleta et al. [22].

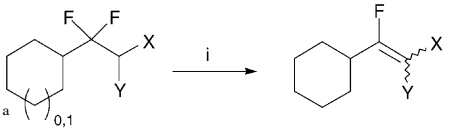
Whilst it is possible to obtain 1:1 adducts from all the difluoroalkenes used, competing telomerisation processes affected the yields of the obtained adducts. Many factors contributing to the degree of telomerisation in various telomerisation processes have been discussed [21] and here, a comparison between free radical addition reactions involving CF_2=CH_2 and CF_2=CCl_2 illustrates the effects of the relative polarities of both the propagating radicals and the alkenes.

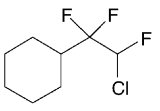
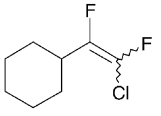
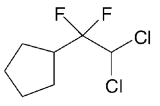
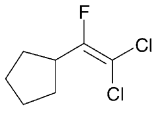
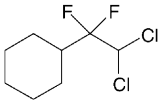
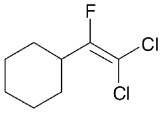
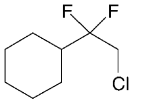
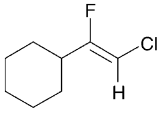
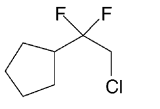
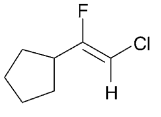
Addition of the nucleophilic radical R to both electrophilic alkenes occurs rapidly but it is the nature of the propagating radicals **21a** and **21b** which lead to differing product distributions(Scheme 3). Radical **21a** is relatively nucleophilic in character and reacts preferentially with a further molecule of the electrophilic alkene CF_2=CH_2 rather than abstracting a hydrogen atom from the electron rich alkane. In contrast, radical **21b**, which has additional electron withdrawing chlorine atom attached to the radical centre is more electrophilic in character than **21a** and so preferentially abstracts a hydrogen atom from the nucleophilic alkane to give the 1:1 adduct.

The experiments described earlier demonstrate that 1:1 adducts derived from difluoroalkenes and alkanes can be synthesised in preparatively useful amounts providing that an excess of the alkane is used. The potential use of the difluorinated adducts as fluorinated building blocks can now be explored and our initial studies have focussed upon the synthesis of several novel fluoroalkenes of general formula R-CF=CXY (X, Y = H, F, Cl).

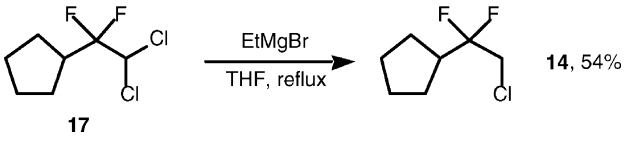
Dehydrofluorination of several of the adducts prepared above was achieved by treatment with *t*-BuOK in THF (Table 2). In each case, the stereochemistry of the alkene was deduced by a consideration of either H–F or F–F coupling constants. On steric grounds, we would expect **5**

Table 2
Dehydrofluorination reactions



Adduct	Temperature (°C)	Product
 **5**	20	 **22**, 55%, *E*:*Z* 4:1
 **17**	−78	 **23**, 63%
 **19**	−78	 **24**, 81%
 **10**	−78	 **25**, 62%, *Z* only
 **14**	−78	 **26**, 63%, *Z* only

[a] Conditions: i, KO*t*Bu, THF; 15 h; temperature as in the table.



Scheme 4.

to give the *Z*-isomer **22**, but this is not the case and an explanation for this result is unclear.

Reduction of adduct **17** to the chlorodifluoro system **14** was accomplished in good yield by reaction with a Grignard reagent (Scheme 4). This synthesis was adapted from methodology described by Okuhara [23] and is envisaged to proceed by an SET mechanism.

3. Conclusion

In summary, addition of carbon radicals, generated by C–H bond homolysis from cycloalkanes, to difluoroethylene derivatives is possible, but telomerisation and, in cases where the alkene bears a chlorine or bromine substituent, halogen atom abstraction compete. Preparatively useful amounts of products such as **5** and **10** can be isolated and the chemistry of these adducts as building blocks for the incorporation of fluorine atoms into organic molecules presents a useful approach.

4. Experimental

All solvents were dried before use by literature procedures. NMR spectra were recorded on a Varian VXR 400S NMR spectrometer with tetramethylsilane and trichlorofluoromethane as internal standards and deuteriochloroform as solvent, unless otherwise stated. In ^{19}F NMR spectra, upfield shifts are quoted as negative. Coupling constants are given in Hertz. Mass spectra were recorded on either a VG 7070E spectrometer or a Fisons VG Trio 1000 spectrometer coupled with a Hewlett Packard 5890 series II gas chromatograph. Accurate mass measurements were performed by the EPSRC Mass Spectrometry Service, Swansea, UK. IR spectra were recorded on a Perkin-Elmer 1600 FT-IR spectrometer using KBr plates while elemental analyses were obtained on either a Perkin-Elmer 240 or a Carlo Erba Elemental Analyser. Melting and boiling points were recorded at atmospheric pressure and are uncorrected. Superscript numbers given as part of boiling point data indicate the pressure (in mmHg) during measurement. Distillations were carried out using a Fischer Spahltrohr MS200 micro-distillation apparatus. The γ-ray irradiations were performed in a purpose built shielded chamber fitted with a cobalt-60 source (500 Ci original activity). Column chromatography was performed on silica gel (Merck no. 1-09385) and TLC analysis was performed on silica gel TLC plates (Merck).

4.1. Reactions of cycloalkanes with difluoroethene derivatives

4.1.1. Di-tert-butyl peroxide initiation—general procedure

An autoclave (ca. 500 ml), fitted with a bursting disc (maximum working pressure approximately 200 bar) was charged with the alkane and di-*tert*-butyl peroxide, evacuated, sealed and degassed by freeze-thawing. The fluoroalkene was degassed separately and transferred to the autoclave at reduced pressure using vacuum line techniques. The autoclave was closed while frozen, transferred to a purpose built chamber and heated at 140 °C for 24 h in a thermostatically controlled rocking furnace. The autoclave was frozen in liquid air and volatile material was collected by vacuum transfer as the autoclave approached room temperature. The autoclave was opened and the crude product mixture was purified by either column chromatography on silica gel or distillation under reduced pressure.

4.1.2. 2-Cyclohexyl-1,1-difluoroethane (3) and 1-cyclohexyl-1,1-difluoroethane (4)

Cyclohexane (44.3 g, 530 mmol), 1,1-difluoroethene (4.2 g, 65 mmol) and DTBP (0.6 g, 4 mmol) after fractional distillation and preparative scale GLC gave a mixture consisting of 2-cyclohexyl-1,1-difluoroethane (**3**) and 1-cyclohexyl-1,1-difluoroethane (**4**) (0.6 g, 8%, 71% conv.) as a colourless liquid in a ratio of 3:1 by GC; bp 149 °C (found: C, 65.1; H, 9.6. $C_8H_{14}F_2$ requires C, 64.9; H, 9.5%); 2-cyclohexyl-1,1-difluoroethane (**3**): δ_H 0.9–1.2 (m), 1.4–1.8 (m), 5.8 (1H, tt, $^2J_{H-F}$ 57, $^3J_{H-H}$ 4.8, CF_2H); δ_C 25.7 (s, C-4), 26.2 (s, C-3), 26.4 (s, C-2), 32.4 (t, $^3J_{C-F}$ 5.3, CH), 41.4 (t, $^2J_{C-F}$ 20, CH_2CF_2H), 116.9 (t, $^1J_{C-F}$ 238, CF_2H); δ_F −113.2 (m); *m/z* (EI^+) 148 (M^+, 4.9%), 83 (100); 1-cyclohexyl-1,1-difluoroethane (**4**): δ_H 0.9–1.2 (m, CH_2), 1.6 (m, CH_3), 1.4–1.8 (m, CH_2); δ_C 21.0 (t, $^2J_{C-F}$ 28, CH_3), 25.7 (s, C-4), 26.2 (s, C-3), 33.1 (s, C-2), 45.4 (t, $^2J_{C-F}$ 24, $CHCF_2$), 125.9 (t, $^1J_{C-F}$ 240, CF_2); δ_F −95.0 (m); *m/z* (EI^+) 109 (4), 83 (100) The remaining material was attributed to telomer formation.

4.1.3. 2-Chloro-1-cyclohexyl-1,1,2-trifluoroethane (5)

Cyclohexane (44.7 g, 530 mmol), chlorotrifluoroethene (6.4 g, 55 mmol) and DTBP (0.6 g, 4 mmol) gave 2-chloro-1-cyclohexyl-1,1,2-trifluoroethane (**5**) (3.5 g, 33%, 99% conv.); bp 212 °C (found: C, 47.9; H, 6.1. $C_8H_{12}ClF_3$ requires C, 47.9; H, 6.0%); δ_H 1.1–1.3 (5H, m, CH_2 axial), 1.6–1.8 (5H, m, CH_2 equatorial), 2.1 (1H, m, $CHCF_2$), 6.2 (1H, ddd, $^2J_{H-F}$ 48, $^3J_{H-F}$ 8.4, $^3J_{H-F}$ 6.4, CFClH); δ_C 24.8 (s, C-4), 25.1 (s, C-3), 25.6 (s, C-2), 40.7 (t, $^2J_{C-F}$ 22, $CHCF_2$), 97.4 (dt, $^1J_{C-F}$ 250, $^2J_{C-F}$ 37, CFClH), 119.4 (td, $^1J_{C-F}$ 251, $^2J_{C-F}$ 24, CF_2); δ_F −119.7 (2F, m, CF_2), −153.7 (1F, dt, $^2J_{F-H}$ 48, $^3J_{F-F}$ 13, CFHCl); *m/z* (EI^+) 202 (M^+, 0.2%), 200 (M^+, 0.8%), 113 (23), 83 (100). Compound **6** was observed by ^1H NMR; δ_H 5.8 ppm (1H, td, $^2J_{H-F}$ 54, $^3J_{H-F}$ 6, $CFClCF_2H$). The remainder of the crude reaction mixture was attributed to higher-adduct formation.

*4.1.4. 2-Bromo-1-cyclohexyl-1,1,2-trifluoroethane (**7**)*

Cyclohexane (50 g, 585 mmol), bromotrifluoroethene (23.0 g, 140 mmol) and DTBP (1.0 g, 7 mmol) gave **7** and bromocyclohexane **8** in a ratio of 3:2 by GC/MS. Fractional distillation gave 2-bromo-1-cyclohexyl-1,1,2-trifluoroethane (**7**) (12.0 g, 35%, 94% conv.) as a colourless liquid; bp 218 °C (found: C, 39.2; H, 4.9. $C_8H_{12}BrF_3$ requires C, 39.2; H, 4.9%); δ_H 1.1–1.3 (5H, m, CH_2 axial), 1.6–1.8 (5H, m, CH_2 equatorial), 2.1 (1H, m, CH), 6.40 (1H, ddd $^2J_{H-F}$ 47, $^3J_{H-F}$ 11, $^3J_{H-F}$ 11, CHBrF); δ_C 24.5 (m, C-4), 25.3 (m, C-3), 25.6 (s, C-2), 40.7 (t, $^2J_{C-F}$ 22, CH), 89.8 (ddd, $^1J_{C-F}$ 259, $^2J_{C-F}$ 40, $^2J_{C-F}$ 35, CHBrF), 119.2 (td, $^1J_{C-F}$ 249, $^2J_{C-F}$ 24, CF_2); δ_F −117.3 (2F, m, CF_2), −156.4 (1F, dt, $^2J_{F-H}$ 47, $^3J_{F-F}$ 17, CFBrH); *m/z* (EI^+) 246 (M^+, 2%), 244 (M^+, 2%), 133 (36), 113 (37), 93 (12), 83 (100).

*4.1.5. 2-Bromo-1-cyclohexyl-1,1-difluoroethane (**9**)*

Cyclohexane (250 g, 3 mol), 1-bromo-2,2-difluoroethene (24 g, 170 mmol) and DTBP (2.5 g, 17 mmol) gave **9** and **8** in a ratio of 5.6:1 by GC/MS. Fractional distillation gave 2-bromo-1-cyclohexyl-1,1-difluoroethane (**9**) (7.1 g, 19%) as a colourless liquid; bp 205 °C (found: C, 42.4; H, 5.8. $C_8H_{13}BrF_2$ requires C, 42.3; H, 5.7%); δ_H 1.1–1.2 (5H, m, CH_2 axial), 1.7–1.8 (5H, m, CH_2 equatorial), 2.0 (1H, m, CH), 3.47 (1H, t, $^3J_{H-F}$ 14, CH_2Br); δ_C 25.3 (t, $^3J_{C-F}$ 4.2, C-4), 25.4 (s, C-3), 25.7 (s, C-2), 30.5 (t, $^2J_{C-F}$ 34, *C*HCF_2), 41.8 (t, $^2J_{C-F}$ 22, CH_2Br), 121.9 (t, $^1J_{C-F}$ 245, CF_2); δ_F −104.1 (m); *m/z* (EI^+) 228 (M^+, 1%), 226 (M^+, 1%), 147 (8), 83 (100).

*4.1.6. 2-Chloro-1-cyclohexyl-1,1-difluoroethane (**10**)*

Cyclohexane (85 g, 1020 mmol), 1-chloro-2,2-difluoroethene (24.2 g, 246 mmol) and DTBP (1.0 g, 7 mmol) gave a mixture of **10**, **11**, chlorocyclohexane **12** and isomers of diadduct **13** in a ratio of 45:3:1:5 by GC/MS. Fractional distillation gave 2-chloro-1-cyclohexyl-1,1-difluoroethane (**10**) (11.9 g, 49%) as a colourless liquid; bp 184 °C (found: C, 52.3; H, 7.2. $C_8H_{13}ClF_3$ requires C, 52.6; H, 7.1%); δ_H 1.0–1.3 (5H, m, CH_2 axial), 1.6–1.8 (5H, m, CH_2 equatorial), 1.97 (1H, m, CH), 3.60 (2H, t, $^3J_{H-F}$ 13, CH_2Cl); δ_C 25.1 (t, $^3J_{C-F}$ 4, C-2), 25.5 (s, C-4), 25.8 (s, C-3), 41.1 (t, $^2J_{C-F}$ 22.4, *C*HCF_2), 43.0 (t, $^2J_{C-F}$ 34.7, *C*H_2Cl), 122.5 (t, $^1J_{C-F}$ 245, CF_2); δ_F −109.4 (m); *m/z* (EI^+) 184 (M^+, 0.57%), 182 (M^+, 2%), 133 (10), 113 (13), 83 (100).

*4.1.7. 2-Chloro-1-cyclopentyl-1,1-difluoroethane (**14**)*

Cyclopentane (33 g, 484 mmol), 1-chloro-2,2-difluoroethene (9.5 g, 97 mmol) and DTBP (1.0 g, 7 mmol) gave a mixture of **14**, **15** and diadducts **16** in a ratio of 50:1:5 by GC/MS. Fractional distillation gave 2-chloro-1-cyclopentyl-1,1-difluoroethane (**14**) (4.0 g, 24%) as a colourless liquid; bp 197 °C (dec) (found: C, 49.7; H, 6.55. $C_7H_{11}ClF_2$ requires C, 49.85; H, 6.5%); δ_H 1.6–1.8 (8H, m, CH_2), 2.6 (1H, m, CH), 3.7 (2H, t, $^3J_{H-F}$ 13, CH_2Cl); δ_C 26.0 (s, C-3), 26.2 (t, $^3J_{C-F}$ 3.8, C-2), 42.6 (t, $^2J_{C-F}$ 23, *C*HCF_2), 44.4 (t, $^2J_{C-F}$ 34, *C*H_2Cl), 122.7 (t, $^1J_{C-F}$ 245, *C*F_2); δ_F −108.9 (dt, $^3J_{H-F}$ 14, $^3J_{H-F}$ 13); *m/z* (EI^+) 119 (47), 99 (78), 91 (16), 77 (22), 69 (100). Compound **15** was observed by ^1H NMR; δ_H 2.3 (1H, td, $^2J_{H-F}$ 14, $^3J_{H-H}$ 6.8, CF_2H).

*4.1.8. 2,2-Dichloro-1-cyclopentyl-1,1-difluoroethane (**17**)*

Cyclopentane (99 g, 1.4 mol), 2,2-dichloro-1,1-difluoroethene (46.6 g, 0.35 mol) and DTBP (1.5 g, 0.011 mol), after distillation under reduced pressure, gave 2,2-dichloro-1-cyclopentyl-1,1-difluoroethane (**17**) (34.2 g, 48%) as a colourless liquid; bp 50 °C (10 mbar) (found: C, 41.1; H, 4.9. $C_7H_{10}Cl_2F_2$ requires C, 41.4; H, 4.9%); ν_{max} (cm^{-1}) 2859 and 2937 (C–H); δ_H 1.6–1.7 (4H, m, CH_2 axial), 1.8–1.9 (4H, m, CH_2 equatorial), 2.7 (1H, m, $CHCF_2$), 5.7 (1H, t, $^3J_{H-F}$ 8.7, $CHCl_2$); δ_C 25.6 (s, C-3), 26.0 (t, $^3J_{C-F}$ 3.4, C-2), 42.1 (t, $^2J_{C-F}$ 22.3, *C*HCF_2), 70.1 (t, $^2J_{C-F}$ 35.3, $CHCl_2$), 121.0 (t, $^1J_{C-F}$ 251, CF_2); δ_F −113.8 (dd, $^3J_{H-F}$ 8.6, $^3J_{H-F}$ 14.7); *m/z* (EI^+) 203 (M^+, 0.27%), 119 (67), 111 (12), 99 (100).

*4.1.9. 2,2-Dichloro-1-cyclohexyl-1,1-difluoroethane (**19**)*

Cyclohexane (52 g, 620 mmol), 1,1-dichloro-2,2-difluoroethene (30 g, 225 mmol) and DTBP (1.0 g, 7 mmol) gave a mixture of **19** and diadducts **20** in a ratio of 6:1 by GC/MS. Fractional distillation gave 2,2-dichloro-1-cyclohexyl-1,1-difluoroethane (**19**) (19.5 g, 40%); bp 206 °C (found: C, 44.0; H, 5.5. $C_8H_{12}Cl_2F_2$ requires C, 44.2; H, 5.5%); δ_H 1.2–1.3 (5H, m, CH_2 axial), 1.8–1.9 (5H, m, CH_2 equatorial), 2.2 (1H, m, CH), 5.8 (1H, t, $^3J_{H-F}$ 9.2, CHCl); δ_C 24.9 (t, $^3J_{C-F}$ 4.1, C-2), 25.3 (s, C-4), 26.6 (s, C-3), 40.9 (t, $^2J_{C-F}$ 23, CH), 69.4 (t, $^2J_{C-F}$ 35, $CHCl_2$), 120.4 (t, $^1J_{C-F}$ 252, CF_2); δ_F −115.9 (dd, $^3J_{H-F}$ 9.0, $^3J_{H-F}$ 8.7); *m/z* (EI^+) 133 (87%), 113 (100), 93 (25).

4.2. γ-Ray initiation—general procedure

A Pyrex Carius tube (ca. 60 ml) was charged with the alkane and degassed three times by freeze-thawing. The fluoroalkene was degassed separately by the same procedure and transferred to the tube, which was cooled in liquid air, at reduced pressure using vacuum line techniques. The tube was sealed under vacuum while frozen and allowed to reach room temperature in a metal sheath. The tube was housed in a purpose built irradiation chamber and irradiated with γ-rays for a period of 10 days to give a total dose of ca. 10 Mrad. The tube was then removed from the chamber, frozen in liquid air and opened. Volatile material was collected via vacuum transfer as the tube approached room temperature and the product mixture was collected and purified by either fractional distillation at reduced pressure (Spaltrohr) or column chromatography on silica gel.

*4.2.1. 2-Bromo-1-cyclohexyl-1,1,2-trifluoroethane (**7**)*

Cyclohexane (8.0 g, 95 mmol) and bromotrifluoroethene (7.7 g, 48 mmol) gave **7** and **8** in a ratio of 1:2 by GLC/MS. Fractional distillation gave 2-bromo-1-cyclohexyl-1,1,2-trifluoroethane (**7**) (2.6 g, 22%, 86% conv.); physical and

spectral data as earlier. Two more by-products with higher retention times were also detected (9 and 15%), but could not be identified.

*4.2.2. 2-Bromo-1-cyclohexyl-1,1-difluoroethane (**9**)*

Cyclohexane (11.5 g, 137 mmol) and 1-bromo-2,2-difluoroethene (4.5 g, 31.5 mmol) gave **9** and **8** in a ratio of 4:1 by GLC/MS. Fractional distillation gave 2-bromo-1-cyclohexyl-1,1-difluoroethane (**9**) (2.6 g, 36%); physical and spectral data as earlier.

*4.2.3. 2,2-Dichloro-1-cyclohexyl-1,1-difluoroethane (**19**)*

Cyclohexane (10.0 g, 119 mmol) and 1,1-dichloro-2,2-difluoroethene (12.7 g, 105 mmol) gave a mixture of 2,2-dichloro-1-cyclohexyl-1,1-difluoroethane (**19**) and diadducts **20** in a ratio of 1:1 by GC/MS. Fractional distillation gave 2,2-dichloro-1-cyclohexyl-1,1-difluoroethane (**19**) (5.1 g, 24%, 100% conv.); physical and spectral data as earlier.

4.2.4. Dehydrofluorination—general procedure

A mixture of dry potassium *tert*-butoxide and THF was cooled to the required temperature under nitrogen. The perfluoroalkyl derivative was added dropwise and stirred for 3 h before being allowed to warm up slowly to room temperature. The reaction mixture was poured into water and neutralised with 10% hydrochloric acid, extracted into dichloromethane, dried ($MgSO_4$) and distilled to give the desired fluoroalkene.

*4.2.5. (Z)- and (E)-1-chloro-2-cyclohexyl-1,2-difluoroethene (**22**)*

Potassium *tert*-butoxide (2.8 g, 25 mmol) and **5** (2.0 g, 10 mmol) in THF (25 ml) at 0 °C gave a mixture of (*Z*)- and (*E*)-1-chloro-2-cyclohexyl-1,2-difluoroethene (**22**) (1.0 g, 55%, *Z*:*E* 4:1 by NMR) as a colourless liquid; bp 190 °C (found: C, 53.4; H, 6.25. $C_8H_{11}ClF_2$ requires C, 53.2; H, 6.1%); *Z* isomer: δ_H 1.0–1.4 (5H, m, CH_2 axial), 1.5–1.8 (5H, m, CH_2 equatorial), 2.3 (1H, dtm, $^3J_{H-F}$ 30, $^3J_{H-H}$ 12, CH); δ_C 25.4 (s, C-4), 25.9 (s, C-3), 28.3 (d, $^3J_{C-F}$ 2.7, C-2), 36.8 (dd, $^2J_{C-F}$ 21, $^3J_{C-F}$ 2.4, C-1), 134.8 (dd, $^1J_{C-F}$ 296, $^2J_{C-F}$ 39, CH*C*F), 146.8 (dd, $^1J_{C-F}$ 255, *C*FCl); δ_F −112.1 (1F, s, C*F*Cl), −144.4 (1F, m, CHC*F*); *E*-isomer: δ_H 1.0–1.4 (5H, m, CH_2 axial), 1.5–1.8 (5H, m, CH_2 equatorial), 2.5 (1H, dtm, $^3J_{H-F}$ 28, $^3J_{H-H}$ 12, CH); δ_C 25.5 (s, C-4), 26.0 (s, C-3), 28.8 (d, $^3J_{C-F}$ 2.3, C-2), 36.8 (dd, $^2J_{C-F}$ 21, $^3J_{C-F}$ 2.4, CH), 135.6 (dd, $^1J_{C-F}$ 282, $^2J_{C-F}$ 57, CH*C*F), 151.4 (dd, $^1J_{C-F}$ 248, *C*FCl); δ_F −128.7 (1F, d, $^3J_{F-F}$ 126, C*F*Cl), −153.8 (1F, dd, $^3J_{F-F}$ 126, $^3J_{F-H}$ 29, CHCF); *m*/*z* (EI^+) 182 (M^+, 8%), 180 (23), 126 (19), 124 (56), 81 (28).

*4.2.6. 1,1-Dichloro-2-cyclopentyl-2-fluoroethene (**23**)*

Potassium *tert*-butoxide (6 g, 54 mmol) and **17** (10 g, 49 mmol) and in THF gave 1,1-dichloro-2-cyclopentyl-2-fluoroethene (**23**) (5.8 g, 63%) as a yellow liquid; bp 185 °C (found: C, 45.6; H, 4.9. $C_7H_9Cl_2F$ requires C, 45.9; H, 4.9%); ν_{max} (cm^{-1}) 1656 (C=C); δ_H 1.4–1.6 (4H, m, CH_2 axial), 1.7–1.9 (4H, m, CH_2 equatorial), 3.1 (1H, dtt, $^3J_{H-F}$ 30.4, $^3J_{H-H}$ 8.4, $^3J_{H-H}$ 8.4, C*H*CF); δ_C 25.9 (s, C-3), 29.3 (s, C-2), 38.8 (d, $^2J_{C-F}$ 24, CH), 105.5 (d,$^2J_{C-F}$ 46.5, CCl_2), 159.5 (d, $^1J_{C-F}$ 263, CF); δ_F −113.4 (d, $^3J_{H-F}$ 30.5); *m*/*z* (EI^+) 182 (M^+, 46%), 142 (24), 141 (20), 140 (36), 105 (28).

*4.2.7. 1,1-Dichloro-2-cyclohexyl-2-fluoroethene (**24**)*

Potassium *tert*-butoxide (0.85 g, 7.6 mmol) and **19** (1.5 g, 6.9 mmol) in THF (15 ml) at −78 °C gave1,1-dichloro-2-cyclohexyl-2-fluoroethene (**24**) (1.1 g, 81%) as a colourless liquid; bp 199 °C (found: C, 48.8; H, 5.7. $C_8H_{11}Cl_2F$ requires C, 48.7; H, 5.6%); δ_H 1.0–1.6 (5H, m, CH_2 axial), 1.6–1.9 (5H, m, CH_2 equatorial), 2.7 (1H, dtt, $^3J_{H-F}$ 28, $^3J_{H-H\,axial}$ 12, $^3J_{H-H\,equatorial}$ 3.6, CHCF); δ_C 25.4 (s, C-4), 25.7 (s, C-3), 28.2 (s, C-2), 38.5 (d, $^2J_{C-F}$ 22, *C*HCF), 105.7 (d, $^2J_{C-F}$ 46, CCl_2), 160.6 (d, $^1J_{C-F}$ 264, CF); δ_F −111.6 (d, $^3J_{H-F}$ 28); *m*/*z* (EI^+) 200 (M^+, 2%), 198 (M^+, 14%), 196 (M^+, 20%), 142 (22), 140 (33), 105 (18), 67 (100).

*4.2.8. (Z)-1-chloro-2-cyclohexyl-2-fluoroethene (**25**)*

Potassium *tert*-butoxide (4.97 g, 44 mmol) and **10** (5.4 g, 30 mmol) in THF (25 ml) at −78 °C gave (*Z*)-1-chloro-2-cyclohexyl-2-fluoroethene (**25**) (3.0 g, 62%) as a colourless liquid; bp 180 °C (found: C, 59.0; H, 7.5. $C_8H_{12}ClF$ requires C, 59.1; H, 7.4%); δ_H 1.1–1.2 (5H, m, CH_2 axial), 1.7–1.8 (5H, m, CH_2 equatorial), 2.1 (1H, m, C*H*CF), 5.23 (1H, d, $^3J_{H-F}$ 26, CHCl); δ_C 25.6 (s, C-4), 25.7 (s, C-3), 29.3 (d, $^3J_{C-F}$ 1.5, C-2), 40.1 (d, $^2J_{C-F}$ 23, *C*HCF), 94.9 (d, $^2J_{C-F}$ 19, CHCl), 164.8 (d, $^1J_{C-F}$ 263, CF); δ_F −108.5 (dd, $^3J_{H-F\,trans}$ 26, $^3J_{H-F}$ 24); *m*/*z* (EI^+) 164 (M^+, 4%), 162 (M^+, 10%), 127 (32), 82 (32), 67 (100).

*4.2.9. (Z)-1-chloro-2-cyclopentyl-2-fluoroethene (**26**)*

Potassium *tert*-butoxide (5.3 g, 47 mmol) and **14** (4 g, 24 mmol) in THF overnight gave (*Z*)-1-chloro-2-cyclopentyl-2-fluoroethene (**26**) (0.9 g, 25%) as a yellow oil; bp 90 °C (10 mbar); (M^+, 148.046. $C_7H_{10}ClF$ requires: M^+, 148.046); δ_H 1.4–1.6 (4H, m, $CH_{2\ axial}$), 1.7–1.9 (4H, m, $CH_{2\ equatorial}$), 5.3 (1H, dd, $^3J_{H-F\,trans}$ 24.8, $^4J_{H-H}$ 0.8, CH); δ_C 25.5 (s, C-3), 26 (s, C-2), 41.4 (d, $^2J_{C-F}$ 23.6, CH), 94.9 (d, $^2J_{C-F}$ 19.4, *C*HCl), 160 (d, $^1J_{C-F}$ 262, *C*F); δ_F −109.8 (2d, $^3J_{F-H}$ 24.4, $^3J_{F-H\,trans}$ 24.8).

*4.2.10. Reduction of 2,2-dichloro-1-cyclopentyl-1,1-difluoroethane (**17**)*

Compound **16** (2.5 g, 12 mmol) was added dropwise to a cooled, stirred solution of C_2H_5MgBr (12 ml, 36 mmol) in THF (25 ml). The reaction mixture was heated at reflux for 24 h and then poured into 10% aqueous sodium hydrogen carbonate. The organic product was extracted with dichloromethane and dried ($MgSO_4$) and solvents were removed under vacuum. Further distillation under reduced pressure gave 2-chloro-1-cyclopentyl-1,1-difluoroethane (**14**) (1.1 g, 54%); spectral and physical data as earlier.

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