A Novel Approach to 2-Chloro-2-fluorostyrenes

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A new general catalytic olefination reaction (COR) of aromatic and heteroaromatic aldehydes and ketones was applied to synthesise 2-chloro-2-fluorostyrenes. The two-stage procedure includes the transformation of carbonyl compounds into hydrazones followed by treatment with $CFCl_3$ mediated by copper catalysis. Trichlorofluoromethane was used as a chlorofluoromethylene transfer reagent. The reaction proceeds stereoselectively and the target alkenes were obtained in high yield. A proposed mechanism for the reaction is discussed.

Introduction

Fluorine-containing drugs and pesticides have achieved an increasing interest in modern bioorganic chemistry due to their remarkable biological activity.[1,2] Extensive studies have been undertaken in order to develop efficient synthetic methodologies to selectively introduce fluorine into various organic compounds.

Earlier we reported a novel catalytic olefination reaction (COR) of carbonyl compounds.[3] It was found that *N*-unsubstituted hydrazones of aromatic and heteroaromatic aldehydes and ketones are quantitatively converted into olefins and *sym*-azines by treatment with polyhalogenalkanes, $CHal_2XY$, in the presence of CuCl as catalyst. This methodology was successfully utilised to synthesise numerous substituted alkenes.[3−7] We showed that various polyhalogenalkanes such as CCl_4,[3,7] $CHBr_3$,[5,7] CBr_4 [6,7] and freons (CF_3CCl_3 and CF_2Cl-$CFCl_2$ [4]) can be used as C_1- or C_2-building blocks for the olefination of a wide range of carbonyl compounds. The target halogen-containing alkenes were obtained in good yields. The remarkable features of this approach are the availability of starting materials, mild reaction conditions and simplicity of reaction procedure, including isolation of the products.

Results and Discussion

In the present paper we report the results of our investigation pertaining to olefination of some aromatic aldehydes (**1a**−**m**) and arylmethylketones (**1n**−**r**) using CFC-11 ($CFCl_3$). We found that $CFCl_3$ can be used as a fluoro-containing C_1-building block for the preparation of 2-chloro-2-fluorostyrenes from aromatic aldehydes and ketones.

A previously reported preparation of β-chloro-β-fluoroalkenes requires a multi-step procedure involving the use of Grignard reagents.[8] The general methodology for β-chloro-β-fluoroalkene preparation has been elaborated by Burton and co-workers and consists of a Wittig-type condensation of carbonyl compounds with a chlorofluoromethylene phosphorous ylide.[9−12] Similar β-bromo-β-fluoroalkenes and β-chloro-β-fluoroalkenes have been used in palladium-catalysed cross-coupling reactions.[13]

Optimization of the Reaction Conditions

We started our study by optimizing the reaction conditions. The hydrazone of 4-chlorobenzaldehyde (**2a**) was used as a model substrate. Recently, we have found the optimal conditions for the synthesis of dichlorostyrenes utilising DMSO as solvent, CuCl (10 mol %) as catalyst and aqueous ammonia as base.[3] It was found that the nature of the solvent and the base used are the main factors affecting the yield of the substituted alkenes. However, previously found conditions for the optimal synthesis of fluorinated alkenes using freons (CF_3CCl_3 and CF_2Cl-$CFCl_2$) were different — ethanol was used as solvent and 1,2-ethylenediamine as base.[4] This peculiar relationship between the nature of the halogenated reagents and the reaction conditions may be linked to a change in catalytic activity brought about by the complexation of copper with solvent and base.

These two types of solvent-base systems were tested in the reaction between **2a** and trichlorofluoroethane. Using DMSO and aqueous ammonia only trace amounts of the

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desired chlorofluoroalkene **3a** were obtained. The major product from the reaction was the corresponding azine **4a** isolated in 30% yield. However, changing the reaction conditions (ethanol as solvent and 1,2-ethylenediamine as base) resulted in the target alkene **3a** being obtained in 58% yield from hydrazone **2a**.

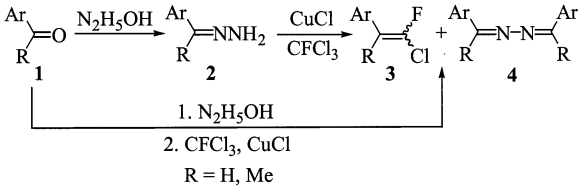
Previously we elaborated a one-pot technique for the synthesis of alkenes from aldehydes without isolation of the hydrazones.[4,14] This procedure is more convenient for the preparation of alkenes due to the poor stability of *N*-unsubstituted hydrazones. It was found that the alkene yield was generally better than that found for the two-stage procedure. This approach was applied to the synthesis of chlorofluorostyrene (**3a**) resulting in an increase in yield to 78% [from 4-chlorobenzaldehyde (**1a**)]. The corresponding azine **4a** was the only side-product obtained (17%).

It should be noted that the olefination reaction proceeds stereoselectively and the *E*-isomer of **3a** is formed predominantly (*E*/*Z* ratio 2.5:1), whereas chlorofluorostyrenes prepared earlier by Burton's approach have lower *E*/*Z* ratios — usually less than 1.6:1.[8,12]

We tried to improve the stereoselectivity of the reaction. To this end, various alcohols were investigated as solvents (MeOH, *i*PrOH, *t*BuOH) and various nitrogen-containing ligands, such as 1,10-phenanthroline and 2,2′-bipyridine were studied. Unfortunately, all our attempts to improve the stereoselectivity were unsuccessful and so we reverted back to using EtOH as the solvent.

Substituent Effects on Reaction Selectivity

Having found the optimal reaction conditions, we attempted to study the synthetic scope of the method for the preparation of 2-chloro-2-fluorostyrenes **3**. We found that a wide variety of aromatic aldehydes (**1a**−**m**) could be converted easily into the corresponding 2-chloro-2-fluorostyrenes (**3**, Scheme 1).



Scheme 1

These results are given in Table 1. Alkene formation generally proceeds in moderate to high yield. The COR process is compatible with many functional groups, including hydroxy-, alkoxy- and nitro-containing systems. Substrates containing both electron-donating and electron-withdrawing substituents on the aromatic ring could be converted into the target alkenes **3**. The corresponding *sym*-azines (**4a**−**d**) were found to be the only side products of the COR process (Scheme 1) and the total isolated yield of products **3** and **4** was usually more than 70%. It was found that the nature of the substituents on the aromatic ring affected the ratio of COR products **3** and **4**; for instance, the electron-donating group in aldehyde **1e** leads to an increase in the yield of azine **4** (increasing to 60%) and a concomitant decrease in the yield of alkene **3**.

Table 1. Synthesis of 2-chloro-2-fluorostyrenes **3** from aromatic aldehydes **1a**−**m**

Ar	Yield [%]			
	Alkene **3**	*E*/*Z* ratio[a]	Azine **4**	**3** + **4**
4-ClC_6H_4, **a**	78	2.6:1	17	95
4-BrC_6H_4, **b**	68	2.4:1	22	90
4-MeC_6H_4, **c**	65	3.3:1	30	95
4-$MeOC_6H_4$, **d**	50	4:1	43	93
4-$Me_2NC_6H_4$, **e**	35	4.2:1	60	95
4-IC_6H_4, **f**	55	2.5:1	22	77
C_6H_5, **g**	62	2.8:1	12	74
4-HOC_6H_4, **h**	54	3.5:1	18	72
4-$O_2NC_6H_4$, **i**	52	2:1	16	68
2,6-$Cl_2C_6H_3$, **j**	68	10:1	8	76
2-BrC_6H_4, **k**	81	2.7:1	9	90
2-$MeOC_6H_4$, **l**	61	3.2:1	11	72
1-Napht, **m**	57	5:1	17	74

[a] By ^1H NMR spectroscopy.

In the case of the aryl methyl ketones (**1n**−**r**), the carbonyl group was less reactive and the corresponding hydrazones could not be prepared and used in situ. We studied the olefination of ketones by trichlorofluoromethane using separately prepared hydrazones. As shown in Table 2, the hydrazones of aromatic ketones **2n**−**r** can be converted into 2-chloro-2-fluoro-1-methylstyrenes (**3n**−**r**) by treatment with $CFCl_3$ under similar conditions (ethanol as solvent and ethylenediamine as base).

Table 2. Synthesis of 2-chloro-2-fluoro-1-methylstyrenes **3n**−**r** from hydrazones **2n**−**r**

Ar	Yield **3** [%]	*E*/*Z* ratio[a]
4-$MeOC_6H_4$, **n**	32	3.6:1
4-MeC_6H_4, **o**	45	4.1:1
4-ClC_6H_4, **p**	61	3.7:1
4-BrC_6H_4, **q**	52	3.0:1
4-$O_2NC_6H_4$, **r**	42	3.0:1

[a] By ^1H NMR spectroscopy.

Examination of Table 1 and 2 reveals that electronic effects and steric factors are important for the stereocontrol of the reaction. Generally, the *E*/*Z* isomer ratio is increased for aldehydes bearing electron-donating substituents on the aromatic ring in comparison to the parent benzaldehyde (**1g**, *E*/*Z* ratio 2.8:1).[4] Conversely, electron-withdrawing groups decrease the *E*/*Z* ratio. Thus, the worst selectivity (*E*/*Z* ratio 2:1) was obtained for 4-nitrobenzaldehyde (**1i**). Both *ortho*- and *para*-substituents affect the isomeric ratio. In addition, the reaction is very sensitive to steric factors. For example, shielding of the carbonyl group combined with the electronic effect of two chlorine atoms as in the case of 2,6-dichlorobenzaldehyde (**1j**) leads to an increase

Table 3. ^1H, ^{19}F NMR chemical shifts and ^1H-^{19}F coupling constants for 2-chloro-2-fluorostyrenes **3a**−**m**

Ar	^1H chemical shifts[a]		^{19}F chemical shifts[b]		$^3J_{H,F}$ (Hz)[b]	
	E	*Z*	*E*	*Z*	*E*	*Z*
4-ClC_6H_4, **a**	5.73	6.28	−73.58	−70.58	30.4	12.3
4-BrC_6H_4, **b**	5.75	6.31	−73.17	−70.33	30.2	12.6
4-MeC_6H_4, **c**	5.70	6.27	−75.38	−72.95	30.8	12.9
4-$MeOC_6H_4$, **d**	5.76	6.35	−77.31	−74.17	31.1	12.9
4-$Me_2NC_6H_4$, **e**	5.62	6.22	−79.45	−76.72	31.3	13.4
4-IC_6H_4, **f**	5.74	6.30	−72.68	−70.09	30.2	12.3
C_6H_5, **g**	5.83	6.39	−74.36	−71.78	30.7	12.9
4-HOC_6H_4, **h**	5.65	6.23	−77.31	−74.26	30.7	12.9
4-$O_2NC_6H_4$, **i**	5.93	6.47	−68.48	−65.23	29.6	12.3
2,6-$Cl_2C_6H_3$, **j**	5.83	6.17	−66.96	−72.08	29.3	8.0
2-BrC_6H_4, **k**	6.22	6.56	−74.21	−70.48	29.6	11.5
2-$MeOC_6H_4$, **l**	6.24	6.63	−75.75	−71.59	31.7	12.6
1-Napht, **m**	5.98	6.55	−74.07	−71.15	30.4	12.9

[a] ^1H NMR (400 MHz, $CDCl_3$/TMS). [b] ^{19}F NMR (376.29 MHz, $CDCl_3$/$CFCl_3$).

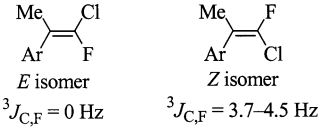
in the *E*/*Z* ratio to 10:1. However the steric effects don't appear to be consistent and are not yet fully understood.

The striking feature of the reaction with the hydrazones of ketones **2n**−**r** is the unexpectedly high stereoselectivity in the formation of the tetrasubstituted alkenes **3n**−**r**. In spite of a seemingly small difference between the steric bulk of the methyl group and that of the aromatic moiety the formation of tetrasubstituted alkenes **3n**−**r** proceeds with significant stereoselectivity and the isomer ratio is greater than 3:1.

Structural Assignment

Selected ^1H and ^{19}F NMR chemical shifts and coupling constants for the chlorofluoroalkenes **3a**−**m** are reported in Table 3. Assignment of the hydrogen atoms in the two isomers was established by the magnitude of their $^3J_{H,F}$ coupling constants. Thus, the *trans* relationship gives rise to a larger coupling (about 31 Hz), while the *cis* coupling is somewhat smaller (about 12 Hz). The signals from the vinyl hydrogen atom, H-1′, in the *E*-isomer are shifted upfield (0.5−0.6 ppm) in comparison with the *Z*-isomer. Similarly, the signals of the vinyl fluorine in the *E*-isomer are shifted upfield (3−4 ppm) in the ^{19}F NMR spectra.

The structure of the isomers of the tetrasubstituted alkenes **3n**−**r** were determined by comparison of the $^3J_{C,F}$ coupling constants and the chemical shift of the fluorine and methyl carbon atoms in the ^{13}C and ^{19}F NMR spectra (Scheme 2), based on literature data for similar compounds containing a 1-methyl-2-fluorovinyl fragment.[15]



Scheme 2

We found that the values of the *cis* and *trans* coupling constants ($^4J_{H,F}$) in this allylic system are similar. However, the coupling ($^3J_{C,F}$ = 3.7−4.5 Hz) for the *cis* isomer is greater than that found for the *trans* isomer (actually no coupling was obtained here). It should also be noted that the signals of the vinyl fluorine in the *E*-isomer are shifted upfield by 0.6−1.2 ppm in the ^{19}F NMR spectra (Table 4), and the signals of the methyl carbon in the *E*-isomer are shifted downfield by 1.3−1.5 ppm in the ^{13}C NMR spectra.

Table 4. ^{19}F chemical shifts for 2-chloro-2-fluoro-1-methylstyrenes **3n**−**r**

Ar	*E* isomer[a]	*Z* isomer[a]
4-$MeOC_6H_4$, **n**	−82.64	−81.50
4-MeC_6H_4, **o**	−82.12	−81.50
4-ClC_6H_4, **p**	−80.68	−79.88
4-BrC_6H_4, **q**	−80.60	−79.81
4-$O_2NC_6H_4$, **r**	−77.68	−77.08

[a] ^{19}F NMR (376.29 MHz, $CDCl_3$/$CFCl_3$).

We analysed the ^{19}F NMR spectra of alkenes **3a**−**r** and found that in the *para*-substituted alkenes, the chemical shifts of the vinyl fluorine and the $^3J_{H,F}$ coupling constants show good linear correlations with Hammett substituent parameters when the σ values[16] were used (Figure 1 and 2). This has been previously observed in the ^{19}F NMR spectra of fluorinated alkenes ArC(H)=C(F)CF_2Cl.[4]

Mechanism of the Reaction

We found that the reaction with $CFCl_3$ is in good agreement with a previously proposed general mechanism for this new catalytic olefination reaction (COR).[4,6,7] The first step of the catalytic cycle is oxidation of hydrazone **2** by Cu^{II} to give the corresponding diazoalkane (Scheme 3). Subsequent copper-catalyzed decomposition of the diazoalkane leads to formation of a copper-carbene complex **I** with evolution of nitrogen. Complex **I** is the key intermediate in the reaction.[4,7] Two routes for its transformation have been found to be possible:[4,7] complex **I** reacts with $CFCl_3$ to

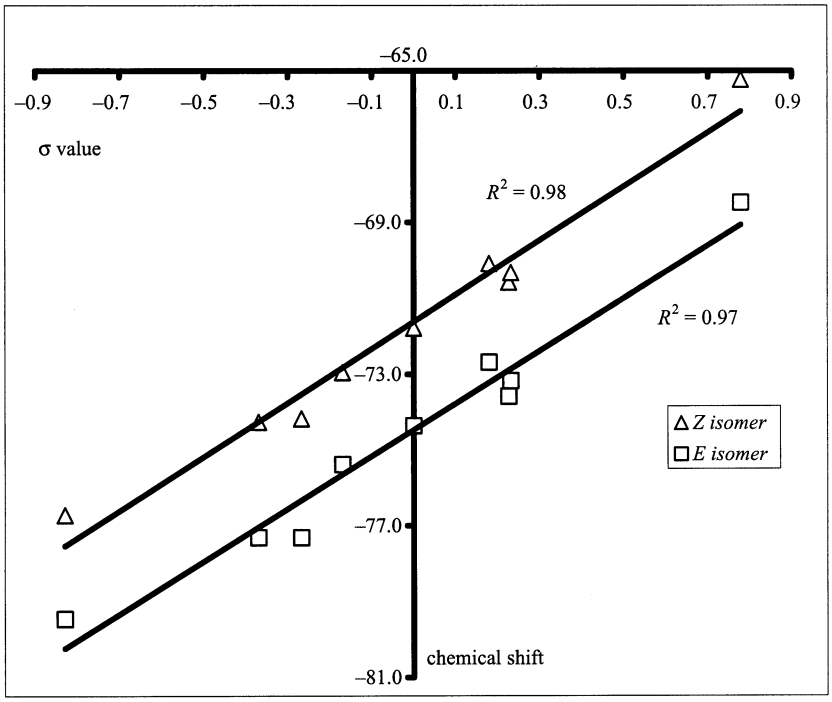


Figure 1. Dependence of chemical shifts of ^{19}F in **3a**−**i** from Hammett constants

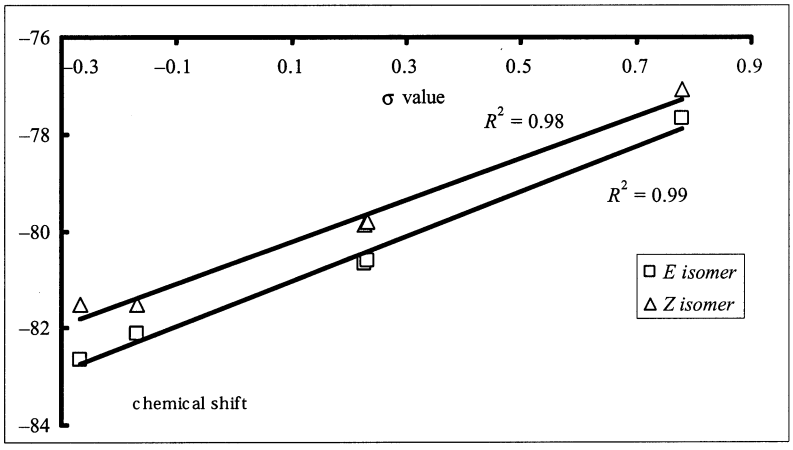
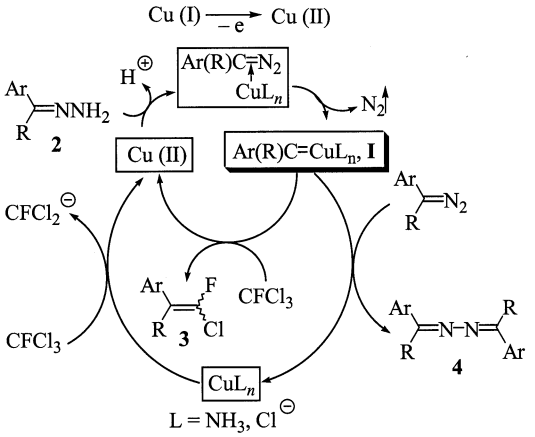


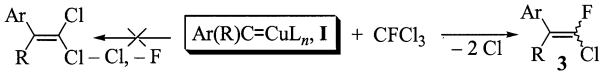
Figure 2. Dependence of chemical shifts of ^{19}F in **3n**−**r** from Hammett constants

produce the target alkene **3** regenerating the catalyst (inside the cycle), or transformation of **I** proceeds by reaction with the diazoalkane to form the *sym*-azine **4** (outside the cycle). The total yield of the products formed by these routes (alkene and azine) is greater than 70% (Table 1). Recently we have investigated in detail the transformations of polyhalogenalkanes, $CHal_2XY$, and found that these compounds are partially reduced under COR conditions (outside cycle).[3−6] This process proceeds via two single-electron transfer (SET) steps (Scheme 4). The corresponding reduced compounds, CHalHXY, were detected in the reaction media.[3−6] In the case of $CFCl_3$, the expected $CFCl_2H$ was not detected, probably due to its high volatility.[2]

It should be noted that two possible types of alkenes could be formed according to the mechanism of the reaction (Scheme 4). Recently we found that both chlorine and fluorine atoms can be eliminated from a freon molecule as in the case of CFC-113 ($CFCl_2$-CF_2Cl) leading to two types of alkenes.[4] The expected product of olefination with $CFCl_3$ (chlorofluoroalkene 3) is formed as a result of elimination of the two chlorine atoms from $CFCl_3$. The abnormal product (dichloroalkene) can be formed as a result of elimination of one chlorine atom and a fluorine atom. However the abnormal product was not detected in the GCMS spectra. The olefination reaction with CFC-11 proceeds with excellent chemoselectivity and only normal



Scheme 3



Scheme 4

products (alkene **3**) were formed. This is in agreement with the C-Hal bond energy.[16]

Conclusion

A new general synthesis of 2-chloro-2-fluorostyrenes and 2-chloro-2-fluoro-1-methylstyrenes based on a COR process has been developed. Formation of the target alkenes proceeds with good stereoselectivity (up to 10:1). The presented synthetic approach permits synthesis of the target alkenes in high yield from readily available and inexpensive starting materials using simple experimental procedures.

Experimental Section

General Remarks: Melting points were determined in sealed capillaries and are uncorrected. NMR spectra were recorded on a Varian VXR-400 spectrometer in $CDCl_3$ with TMS as an internal standard. IR spectra were obtained with UR-20 spectrometer. Column and TLC chromatography was performed on silica gel Merck 60 and Merck $60F_{254}$ plates, respectively. Mass-spectra were recorded on an HP5890 mass spectrometer with the 5989x-G detector.

Hydrazones **2a**,[3] **2n**,[17] **2o**,[17] **2p**,[18] **2q**,[19] **2r**[20] were prepared by the literature procedures.

Preparation of 2-Chloro-2-fluorostyrenes 3a−m: A solution of the aromatic aldehyde (5 mmol) in EtOH (20 mL) was added dropwise to a solution of hydrazine hydrate (5 mmol, 0.25 mL) in EtOH (5 mL) and the mixture was stirred until all the aldehyde had been consumed (3 hours, TLC monitoring). Then, freshly purified CuCl[21] (50 mg, 0.5 mmol) and 1,2-ethylenediamine (1.7 mL) were added. After 10 minutes $CFCl_3$ (0.85 mL, 10 mmol) was added dropwise whilst maintaining the temperature at 20 °C by means of a water bath. The reaction mixture was stirred for 24 h and quenched with hydrochloric acid (5%, 300 mL). The reaction products were extracted with CH_2Cl_2 (50 mL ×3) and dried over sodium sulfate. The CH_2Cl_2 was evaporated and the residue was purified by column chromatography. The *E*- and *Z*-isomers could not be separated by column chromatography.

Preparation of 2-Chloro-2-fluoro-1-methylstyrenes 3n−r: Freshly purified CuCl[21] (50 mg, 0.5 mmol) and 1,2-ethylenediamine (1.7 mL) were added to a solution of freshly prepared hydrazone (5 mmol) in ethanol (25 mL). Then, $CFCl_3$ (0.85 mL, 10 mmol) was added dropwise, maintaining the temperature at 20 °C by means of a water bath. The reaction mixture was stirred for 24 h and then quenched with hydrochloric acid (5%, 300 mL). The reaction products were extracted with CH_2Cl_2 (50 mL ×3) and dried over sodium sulfate. The CH_2Cl_2 was evaporated and the residue was purified by column chromatography.

All new compounds gave satisfactory 400 MHz ^1H NMR ($CDCl_3$, Me_4Si), ^{19}F NMR ($CDCl_3$, $CFCl_3$) and 100 MHz ^{13}C NMR ($CDCl_3$) and IR spectroscopic data. ^{19}F NMR spectroscopic data for alkenes **3a−r** are reported in Table 3 and 4. The known compounds **3a**,[8] **3b**,[22] **3c**,[8] **3d**,[8] **3g**[9] were identified by comparison of physical and spectroscopic data with those previously reported data.

***N*-[4-(2-Chloro-2-fluorovinyl)phenyl]-*N*,*N*-dimethylamine (3e):** This compound was obtained as a mixture of *E* and *Z* isomers (4.2:1 after purification); colourless oil (340 mg, 35%); R_f (Hexane/CH_2Cl_2 1:1) 0.55.%. IR (Nujol): $\tilde{\nu}$ = 1610 cm^{-1} (C=C). ***E* isomer**: ^1H NMR: δ = 2.89 (s, 6 H, Me), 5.62 (d, $^3J_{H,F}$ = 31.3 Hz, 1 H, −CH=), 6.60 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar), 7.20 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^1H NMR: δ = 2.89 (s, 6 H, Me), 6.22 (d, $^3J_{H,F}$ = 13.4 Hz, 1 H, −CH=), 6.62 (d, $^3J_{H,H}$ = 9.1 Hz, 2 H, Ar), 7.29 (d, $^3J_{H,H}$ = 9.1 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 40.2 (Me), 106.9 (d, $^2J_{C,F}$ = 26.1 Hz, CH=, *Z* isomer), 107.5 (d, $^2J_{C,F}$ = 11.7 Hz, CH=, *E* isomer), 112.1, 120.2, 128.9, 139.0 (d, $^1J_{C,F}$ = 293.5 Hz, CFCl, *Z* isomer), 141.7 (d, $^1J_{C,F}$ = 309.1 Hz, CFCl, *E* isomer), 149.7 (C−N) ppm. $C_{10}H_{11}ClFN$ (199.7): calcd. C 60.16, H 5.55; found C 59.88, H 5.39.

1-(2-Chloro-2-fluorovinyl)-4-iodobenzene (3f): This compound was obtained as a mixture of *E* and *Z* isomers (2.5:1 after purification); colourless crystals (765 mg, 55%); − IR (Nujol): $\tilde{\nu}$ = 1620 cm^{-1} (C=C). R_f (Hexane) 0.6. ***E* isomer**: ^1H NMR: δ = 5.74 (d, $^3J_{H,F}$ = 30.2 Hz, 1 H, −CH=), 7.11 (d, $^3J_{H,H}$ = 8.2 Hz, 2 H, Ar), 7.66 (d, $^3J_{H,H}$ = 8.2 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^1H NMR: δ = 6.30 (d, $^3J_{H,F}$ = 12.3 Hz, 1 H, −CH=), 7.19 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, Ar), 7.67 (d, $^3J_{H,H}$ = 8.4 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 93.2 (C−I), 106.4 (d, $^2J_{C,F}$ = 29.0 Hz, CH=, *Z* isomer), 106.8 (d, $^2J_{C,F}$ = 9.2 Hz, CH=, *E* isomer), 129.7, 130.0, 130.6, 137.8, 142.1 (d, $^1J_{C,F}$ = 299.1 Hz, =CClF, *Z* isomer), 145.3 (d, $^1J_{C,F}$ = 312.8 Hz, =CClF, *E* isomer) ppm. C_8H_5ClF (282.5): calcd. C 34.01, H 1.78; found C 33.86, H 1.73.

4-(2-Chloro-2-fluorovinyl)phenol (3h): This compound was obtained as a mixture of *E* and *Z* isomers (3.5:1 after purification); colourless oil (466 mg, 54%); R_f (CH_2Cl_2) 0.5. IR (Nujol): $\tilde{\nu}$ = 1615 cm^{-1} (C=C). ***E* isomer**: ^1H NMR: δ = 5.53 (s, 1 H, OH), 5.65 (d, $^3J_{H,F}$ = 30.7 Hz, 1 H, −CH=), 6.72 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, Ar), 7.19 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^1H NMR: δ = 5.53 (s, 1 H, OH), 6.23 (d, $^3J_{H,F}$ = 12.9 Hz, 1 H, −CH=), 6.75 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar), 7.27 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 106.6 (d, $^2J_{C,F}$ = 29.0 Hz, =CH, *Z* isomer), 107.0 (d, $^2J_{C,F}$ = 10.7 Hz, =CH, *E* isomer), 115.3, 124.7, 129.3, 140.4 (d, $^1J_{C,F}$ = 296.0 Hz, CClF, *Z* isomer), 143.2 (d,

$^1J_{C,F}$ = 309.8 Hz, CClF, *E* isomer), 154.9 (COH) ppm. C_8H_6ClFO (172.6): calcd. C 55.67, H 3.50; found C 55.48, H 3.46.

1-(2-Chloro-2-fluorovinyl)-4-nitrobenzene (3i): This compound was obtained as a mixture of *E* and *Z* isomers (2:1 after purification); colourless crystals (522 mg, 52%); R_f (Hexane/CH_2Cl_2 1:1) 0.60. IR (Nujol): $\tilde{\nu}$ = 1610 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 5.93 (d, $^3J_{H,F}$ = 29.6 Hz, 1 H, −CH=), 7.53 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar), 8.19 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 6.47 (d, $^3J_{H,F}$ = 12.3 Hz, 1 H, −CH=), 7.63 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, Ar), 8.21 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 105.9 (d, $^2J_{C,F}$ = 10.4 Hz, CH=, *Z* isomer), 106.3 (d, $^2J_{C,F}$ = 10.4 Hz, CH=, *E* isomer), 124.0, 128.6, 128.9, 138.3 (CNO_2), 147.5 (d, $^1J_{C,F}$ = 315.0 Hz, =CFCl, *E* isomer) ppm. $C_8H_5ClFNO_2$ (201.6): calcd. C 47.67, H 2.50; found C 47.81, H 2.63.

1,3-Dichloro-2-(2-chloro-2-fluorovinyl)benzene (3j): This compound was obtained as a mixture of *E* and *Z* isomers (10:1 after purification); colourless oil (765 mg, 68%); R_f (Hexane) 0.6. IR (Nujol): $\tilde{\nu}$ = 1610 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 5.83 (d, $^3J_{H,F}$ = 29.3 Hz, 1 H, −CH=), 7.19 (t, $^3J_{H,H}$ = 8.5 Hz, 1 H, Ar), 7.32 (d, $^3J_{H,H}$ = 8.5 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 6.17 (d, $^3J_{H,F}$ = 8.0 Hz, 1 H, −CH=), 7.18 (t, $^3J_{H,H}$ = 8.3 Hz, 1 H, Ar), 7.27 (d, $^3J_{H,H}$ = 8.3 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 102.3 (d, $^2J_{C,F}$ = 15.3 Hz, CH=, *E* isomer), 127.9, 128.0, 129.6, 135.2, 145.8 (d, $^1J_{C,F}$ = 311.3 Hz, CFCl, *E* isomer) ppm. $C_8H_4Cl_3F$ (225.5): calcd. C 42.61, H 1.79; found C 42.46, H 1.76.

1-Bromo-2-(2-chloro-2-fluorovinyl)benzene (3k): This compound was obtained as a mixture of *E* and *Z* isomers (2.7:1 after purification); colourless oil (947 mg, 81%); R_f (Hexane) 0.55. IR (Nujol): $\tilde{\nu}$ = 1620 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 6.22 (d, $^3J_{H,F}$ = 29.6 Hz, 1 H, −CH=), 7.26−7.34 (m, 4 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 6.56 (d, $^3J_{H,F}$ = 11.5 Hz, 1 H, −CH=), 7.26−7.34 (m, 4 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 106.4 (d, $^2J_{C,F}$ = 9.1 Hz, CH=, *E* isomer), 122.9, 124.3 (=CBr), 127.5, 129.1, 129.9, 132.9, 145.9 (d, $^1J_{C,F}$ = 313.0 Hz, CFCl, *E* isomer), 143.2 (d, $^1J_{C,F}$ = 300.0 Hz, CFCl, *Z* isomer) ppm. C_8H_5BrClF (235.5): calcd. C 40.80, H 2.14; found C 40.54, H 2.03.

1-(2-Chloro-2-fluorovinyl)-2-methoxybenzene (3l): This compound was obtained as a mixture of *E* and *Z* isomers (3.2:1 after purification); colourless oil (568 mg, 61%); R_f (Hexane) 0.20. IR (Nujol): $\tilde{\nu}$ = 1615 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 3.82 (s, 3 H, MeO), 6.24 (d, $^3J_{H,F}$ = 31.7 Hz, 1 H, −CH=), 6.8−7.6 (m, 4 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 3.82 (s, 3 H, MeO), 6.63 (d, $^3J_{H,F}$ = 12.6 Hz, 1 H, −CH=), 6.85−7.53 (m, 4 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 55.4 (MeO), 101.5 (d, $^2J_{C,F}$ = 11.7 Hz, CH=, *Z* isomer), 101.5 (d, $^2J_{C,F}$ = 9.1 Hz, CH=, *E* isomer), 103.9, 110.4, 110.5, 120.7, 129.0, 141.7 (d, $^1J_{C,F}$ = 297.4 Hz, CFCl, *Z* isomer), 144.3 (d, $^1J_{C,F}$ = 311.7 Hz, CFCl, *E* isomer), 155.8 (*C*OMe) ppm. C_9H_8ClFO (186.6): calcd. C 57.93, H 4.32; found C 58.20, H 4.17.

2-(2-Chloro-2-fluorovinyl)naphthalene (3m): This compound was obtained as a mixture of *E* and *Z* isomers (5:1 after purification); colourless oil (591 mg, 57%); R_f (Hexane) 0.6. IR (Nujol): $\tilde{\nu}$ = 1620 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 5.98 (d, $^3J_{H,F}$ = 30.4 Hz, 1 H, −CH=), 7.45−7.58 (m, 3 H, Napht), 7.78−7.84 (m, 4 H, Napht) ppm. ***Z* isomer**: ^{1}H NMR: δ = 6.55 (d, $^3J_{H,F}$ = 12.9 Hz, 1 H, −CH=), 7.45−7.58 (m, 3 H, Napht), 7.78−7.84 (m, 4 H, Napht) ppm. For mixture of isomers ^{13}C NMR: δ = 107.5 (d, $^2J_{C,F}$ = 12.2 Hz, -CH=, *Z* isomer), 107.8 (d, $^2J_{C,F}$ = 12.2 Hz, -CH=, *E* isomer), 125.5, 125.6, 127.0, 127.3, 127.6. 128.0, 128.1, 128.3, 128.6, 129.5, 143.3 (d, $^1J_{C,F}$ = 297.6 Hz, CFCl, *Z* isomer), 144.9 (d, $^1J_{C,F}$ = 303.7 Hz, CFCl, *E* isomer) ppm. $C_{12}H_8ClF$ (206.6): calcd. C 69.75, H 3.90; found C 69.53, H 3.77.

1-(2-Chloro-2-fluoro-1-methylvinyl)-4-methoxybenzene (3n): This compound was obtained as a mixture of *E* and *Z* isomers (3.6:1 after purification); colourless oil (328 mg, 32%); R_f (Hexane) 0.3. IR (Nujol): $\tilde{\nu}$ = 1610 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 1.98 (d, $^4J_{H,F}$ = 3.4 Hz, 3 H, Me), 3.69 (s, 3 H, OMe), 6.71 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar), 7.14 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 1.98 (d, $^4J_{H,F}$ = 4.2 Hz, 3 H, Me), 3.70 (s, 3 H, OMe), 6.72 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, Ar), 7.09 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 15.1 (d, $^3J_{C,F}$ = 3.7 Hz, Me, *Z* isomer), 16.5 (Me, *E* isomer), 52.6 (MeO), 94.1, 110.9 (d, $^2J_{C,F}$ = 12.7 Hz, −C=, *E* isomer), 111.6, 126.7, 138.4 (d, $^1J_{C,F}$ = 297.0 Hz, CFCl, *Z* isomer), 138.5 (d, $^1J_{C,F}$ = 300.0 Hz, CFCl, *E* isomer) ppm. $C_{10}H_{10}ClFO$ (200.6): calcd. C 59.86, H 5.02; found C 59.68, H 5.14.

1-(2-Chloro-2-fluoro-1-methylvinyl)-4-methylbenzene (3o): This compound was obtained as a mixture of *E* and *Z* isomers (4.1:1 after purification); colourless oil (410 mg, 45%); R_f (Hexane) 0.7. IR (Nujol): $\tilde{\nu}$ = 1615 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 1.95 (d, $^4J_{H,F}$ = 3.2 Hz, 3 H, =C-*Me*), 2.22 (s, 3 H, Me), 6.97 (d, $^3J_{H,H}$ = 8.3 Hz, 2 H, Ar), 7.08 (d, $^3J_{H,H}$ = 8.3 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 1.92 (d, $^4J_{H,F}$ = 4.5 Hz, 3 H, =C-*Me*), 2.23 (s, 3 H, Me), 6.97 (d, $^3J_{H,H}$ = 8.3 Hz, 2 H, Ar), 7.04 (d, $^3J_{H,H}$ = 8.3 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 15.1 (d, $^3J_{C,F}$ = 4.5 Hz, *Me*-C=, *Z* isomer) 16.4 (*Me*-C=, *E* isomer), 19.1 (*Me*-Ar), 110.6 (d, $^2J_{C,F}$ = 12.7 Hz, −C=, *E* isomer), 112.0 (d, $^2J_{C,F}$ = 20.2 Hz, −C=, *Z* isomer), 125.6, 126.0, 126.8, 131.3, 138.4 (d, $^1J_{C,F}$ = 297.7 Hz, CFCl, *Z* isomer), 138.9 (d, $^1J_{C,F}$ = 300.0 Hz, CFCl, *E* isomer) ppm. $C_{10}H_{10}ClF$ (184.6): calcd. C 65.05, H 5.46; found C 64.89, H 5.37.

1-Chloro-4-(2-chloro-2-fluoro-1-methylvinyl)benzene (3p): This compound was obtained as a mixture of *E* and *Z* isomers (3.7:1 after purification); colourless oil (580 mg, 61%); R_f (Hexane) 0.65. IR (Nujol): $\tilde{\nu}$ = 1610 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 2.00 ($^4J_{H,F}$ = 3.2 Hz, 3 H, Me), 7.15−7.28 (m, 4 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 1.98 ($^4J_{H,F}$ = 4.1 Hz, 3 H, Me), 7.15−7.28 (m, 4 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 17.0 (d, $^3J_{C,F}$ = 3.9 Hz, Me, *Z* isomer), 18.4 (Me, *E* isomer), 112.1 (d, $^2J_{C,F}$ = 11.7 Hz, −C=, *E* isomer), 113.5 (d, $^2J_{C,F}$ = 20.9 Hz, −C=, *Z* isomer), 128.5, 129.1, 129.6 (CCl), 133.4, 140.8 (d, $^1J_{C,F}$ = 298.7 Hz, CFCl, *Z* isomer), 141.6 (d, $^1J_{C,F}$ = 300.0 Hz, CFCl, *E* isomer) ppm. $C_9H_7Cl_2F$ (205.1): calcd. C 52.72, H 3.44; found C 52.61, H 3.32.

1-Bromo-4-(2-chloro-2-fluoro-1-methylvinyl)benzene (3q): This compound was obtained as a mixture of *E* and *Z* isomers 3.0:1 (after purification); colourless oil (643 mg, 52%); R_f (Hexane) 0.65. IR (Nujol): $\tilde{\nu}$ = 1610 cm^{-1} (C=C). ***E* isomer**: ^{1}H NMR: δ = 1.99 (d, $^4J_{H,F}$ = 3.9 Hz, 3 H, Me), 7.11 (d, $^3J_{H,H}$ = 7.8 Hz, 2 H, Ar), 7.36 (d, $^3J_{H,H}$ = 7.8 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^{1}H NMR: δ = 1.98 (d, $^4J_{H,F}$ = 4.9 Hz, 3 H, Me), 7.07 (d, $^3J_{H,H}$ = 7.8 Hz, 2 H, Ar), 7.37 (d, $^3J_{H,H}$ = 7.8 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = 14.9 (d, $^3J_{C,F}$ = 3.7 Hz, Me, *Z* isomer), 16.3 (Me, *E* isomer), 109.7 (d, $^2J_{C,F}$ = 12.7 Hz, −C=, *E* isomer), 111.3 (d, $^2J_{C,F}$ = 30.0 Hz, −C=, *Z* isomer), 127.2, 127.6, 129.4, 132.8, 138.8 (d, $^1J_{C,F}$ = 298.5 Hz, CFCl, *Z* isomer), 139.6 (d, $^1J_{C,F}$ = 301.5 Hz, CFCl, *E* isomer) ppm. C_9H_7BrClF (249.5): calcd. C 43.32, H 2.83; found C 43.16, H 2.75.

1-(2-Chloro-2-fluoro-1-methylvinyl)-4-nitrobenzene (3r): This compound was obtained as a mixture of *E*-*Z* isomers 3.0:1 (after puri-

fication); slight yellow oil (447 mg, 42%); R_f (Hexane) 0.15. IR (Nujol): $\tilde{\nu}$ = 1615 cm^{-1} (C=C). ***E* isomer**: ^1H NMR: δ = 2.12 ($^4J_{H,F}$ = 3.3 Hz, 3 H, Me), 7.51 (d, $^3J_{H,H}$ = 9.1 Hz, 2 H, Ar), 8.19 (d, $^3J_{H,H}$ = 9.1 Hz, 2 H, Ar) ppm. ***Z* isomer**: ^1H NMR: δ = 2.09 ($^4J_{H,F}$ = 4.1 Hz, 3 H, Me), 7.48 (d, $^3J_{H,H}$ = 11.6 Hz, 2 H, Ar), 8.19 (d, $^3J_{H,H}$ = 11.6 Hz, 2 H, Ar) ppm. For mixture of isomers ^{13}C NMR: δ = (100 MHz, $CDCl_3$; Me_4Si) 17.2 (d, $^3J_{C,F}$ = 3.7 Hz, Me, *Z* isomer), 18.5 (Me, *Z* isomer), 113.1 (d, $^2J_{C,F}$ = 12.7 Hz, −C=, *E* isomer), 114.3 (d, $^2J_{C,F}$ = 26.0 Hz, −C=, *Z* isomer), 125.5, 131.1, 131.6, 140.8 (d, $^1J_{C,F}$ = 298.9 Hz, CFCl, *Z* isomer), 141.6 (d, $^1J_{C,F}$ = 300.5 Hz, CFCl, *E* isomer), 147.5 (C−NO_2) ppm. $C_9H_7ClFNO_2$ (215.6): calcd. C 50.14, H 3.27; found C 50.01, H 3.14.

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