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</tr>
<tr>
<td>Publication date</td>
<td>2011-04-07</td>
</tr>
<tr>
<td>Type of publication</td>
<td>Article (peer-reviewed)</td>
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| Link to publisher's version | [http://pubs.rsc.org/en/content/articlelanding/2011/ob/c0ob00805b](http://pubs.rsc.org/en/content/articlelanding/2011/ob/c0ob00805b)  
[http://dx.doi.org/10.1039/C0OB00805B](http://dx.doi.org/10.1039/C0OB00805B) |
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Addition-substitution reactions of 2-thio-3-chloroacrylamides with carbon, nitrogen, oxygen, sulfur and selenium nucleophiles

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Abstract:

Synthetically versatile conjugate addition of a range of carbon, nitrogen, oxygen, sulfur and selenium nucleophiles to the highly functionalised 2-thio-3-chloroacrylamides is described. The stereochemical and synthetic features of this transformation are discussed in detail. In most instances, the nucleophile replaces the chloro substituent with retention of stereochemistry. With the oxygen nucleophiles, a second addition can occur leading to acetals, while with the nitrogen nucleophiles, E-Z isomerism occurs in the resulting enamine derivatives. The ratio of the E/Z isomers can be rationalised on the basis of the substituent and the level of oxidation.

Introduction

Nucleophilic addition to conjugatively unsaturated systems is a well established synthetic method. 1-4 Alkenes bearing electron-withdrawing groups such as esters, amides, ketones,
sulfones or nitriles can react with a wide range of nucleophiles (both carbon-based or heteroatom-based) in a conjugate fashion to generate a stabilised anion which is quenched by protonation or reaction with an electrophile. While α,β-unsaturated amides undergo conjugate addition they are, in general, the least reactive Michael acceptors and usually require basic conditions or acid catalysis.\(^2\)

The presence of a leaving group on the β-carbon offers another possibility for reaction of the stabilised anion.\(^5\) Displacement of the leaving group with reformation of the conjugated system can be envisaged as illustrated in Scheme 1.

The rate of nucleophilic addition reactions is determined by the electrophilicity of the β-carbon. Rappoport has studied the nucleophilic substitution of vinylic halides bearing α-electron withdrawing groups, and has found that the reaction rate increases when the β-substituent is changed from bromine to chlorine to fluorine.\(^6\)-\(^8\) This is due to the increasing electronegativity from bromine to fluorine rendering the β-carbon more electrophilic, rather than the leaving group ability, which increases in the reverse order.

Nearly complete retention of configuration has been observed in the substitution reactions of many vinyl chlorides and bromides.\(^9\)-\(^12\) However, partial or complete stereoconvergence is also possible,\(^13,14\) particularly when the carbanionic carbon bears two strongly electron withdrawing groups. The retention or loss of stereochemistry may be rationalised by relating the ability of the C\(_2\)-C\(_3\) single bond to rotate to the stability of the carbanion. The greater the stabilisation, the more time exists for rotation and therefore stereoconvergence to occur (Scheme 2).\(^6\) Conversely, any factor that reduces the stability of the carbanion increases the possibility of retention. Anionic nucleophiles enhance leaving group expulsion and therefore promote retention.
We have recently reported the highly efficient and stereoselective transformation of $\alpha$-thioamides to the corresponding $\alpha$-thio-$\beta$-chloroacrylamide derivatives on treatment with NCS.\textsuperscript{15} The chemoselective and stereoselective oxidation of the $\beta$-chloroacrylamides to the sulfoxide and sulfone levels of oxidation has extended the scope of this methodology.\textsuperscript{16,17} The $\alpha,\beta$-unsaturated system of the $\beta$-chloroacrylamides contains substituents with considerably different electronic properties. The amide group is electron withdrawing both inductively and by resonance delocalisation, although this effect is reduced somewhat by delocalisation of the nitrogen lone pair into the carbonyl. The sulfide substituent is inductively electron withdrawing, but can donate electron density to the $\beta$-carbon by resonance. Likewise, the chloride group is electron withdrawing inductively but can be resonance donating. While the sulfide group can confer nucleophilic character to the $\beta$-carbon, the combined effects of the amide and chloride groups are more significant, and overall lead to an electrophilic $\beta$-carbon.

A wide range of reaction pathways can be envisaged with these highly functionalised acrylamide derivatives, including Diels-Alder cycloadditions and 1,3-dipolar cycloadditions.\textsuperscript{18,19} Potentially one of the most interesting and synthetically useful pathways is the addition of nucleophiles to the $\beta$-carbon. Conjugate addition followed by chloride displacement would be expected to lead to $\beta$-substitution. A wide range of nucleophiles can be envisaged, and if this substitution is widely applicable, it would allow access to a wide variety of differently substituted acrylamide derivatives.

Herein, we report the addition of a range of carbon, nitrogen, oxygen and sulfur based nucleophiles to the $\beta$-chloroacrylamides. We were particularly interested to determine if the product of a single nucleophilic addition with chloride displacement would be observed, or if a second addition of the nucleophile to the resulting Michael acceptor would occur. Furthermore, determination of the stereochemical features of the transformations was of interest (Scheme 3).
Results and Discussion

Carbon Based Nucleophiles

As the Michael addition of active methylene compounds to conjugated systems is one of the oldest and more useful carbon-carbon bond-forming reactions,\textsuperscript{1,20} nucleophilic addition of the enolates of diethyl malonate and ethyl acetoacetate to the $\beta$-chloroacrylamides was studied initially. This work was later extended to the cyclohexanone enolate and a range of organocuprates.

\textbf{Stabilised enolates}

Investigation of the reaction of the $\beta$-chloroacrylamide \textbf{1a} with the diethyl malonate anion, generated using a range of bases and reaction conditions, was undertaken. While the employment of 2.1 equivalents of sodium ethoxide in ethanol with 2 equivalents of diethyl malonate yielded the substitution product \textbf{2a}, excess diethyl malonate was present in the product and a low yield (45\%) was achieved. Use of a reduced amount of sodium ethoxide ($< 2 \text{ eq.}$) or employment of other bases such as sodium hydride or potassium $t$-butoxide either led to incomplete reaction or side-product formation. Optimisation of the process was undertaken, and ultimately the addition of the lithium salt of diethyl
malonate (prepared from reaction of 1.1 equivalents of diethyl malonate with 1.05 equivalents of LDA in THF at 0 °C) to 1a in THF at 0 °C for 1 h afforded the corresponding adduct 2a in 80% yield. Extension of this reaction of the anion of diethyl malonate with the \( \beta \)-chloroacrylamides 1b and 1c gave the extended acrylamides 2b and 2c in yields of 72% and 88% respectively (Table 1). This indicates that the methodology is compatible with both aryl and benzyl amides, signifying that altering the acidity of the NH of the amides is not detrimental to the substitution process.

**Table 1 Michael Addition of the Enolate of Diethyl Malonate**

<table>
<thead>
<tr>
<th>( \beta )-Cl</th>
<th>( R^1 )</th>
<th>Product</th>
<th>Z:E</th>
<th>% Yield*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Tol</td>
<td>2a</td>
<td>27:1</td>
<td>80</td>
</tr>
<tr>
<td>1b</td>
<td>(S)-CH(CH(_3))Ph</td>
<td>2b</td>
<td>30:1</td>
<td>72</td>
</tr>
<tr>
<td>1c</td>
<td>Bn</td>
<td>2c</td>
<td>15:1</td>
<td>88</td>
</tr>
</tbody>
</table>

* Isolated yield after chromatographic purification.

The malonate adducts 2a–2c were isolated predominantly as one stereoisomer, with trace amounts of a minor isomer (~3-4%) in each case. The isomers were not separable by chromatography. Under the basic conditions, \( E-Z \) interconversion can be readily envisaged via an extended enolate. While the stereochemistry of the malonate adducts has not been definitively confirmed, the major isomer is believed to have \( Z \)-stereochemistry. In the \(^1\)H NMR spectra, the signals for the characteristic vinylic proton in the two isomers are clearly resolved, appearing at \( \delta_H \) 7.60-7.75 ppm in the major isomer and at higher field at \( \delta_H \) 6.78-6.82 ppm in the minor isomer, reflecting a greater distortion from planarity in the conjugated system in the more sterically crowded \( E \)-isomer. Furthermore, the proton between the two ester groups in the minor isomer is significantly deshielded, consistent with hydrogen bonding to the amide oxygen (see for example Scheme 4).
Alkylation of the malonate adducts can be envisaged at either the α- or γ-position, and a brief exploration was undertaken to establish the potential synthetic utility of this transformation (see Supporting Information).

The next carbon-based nucleophile explored was the enolate of ethyl acetoacetate, with the outcome of the reaction dependant on the nature of the basic conditions employed (Scheme 5).

Addition of a solution of the β-chloroacrylamide 1a in ethanol to a solution of the sodium enolate of ethyl acetoacetate (prepared by reaction of 2 equivalents of sodium ethoxide with 2 equivalents of ethyl acetoacetate in ethanol) afforded the enol form of the substituted product 4a in 57% yield following trituration in cold hexane. The enol form is presumably favoured due to extended conjugation and hydrogen bonding.
In contrast, employment of LDA as base led to the isolation of the deacylated compound 5a in 22% yield following purification by chromatography on silica gel (Scheme 5). Interestingly, this deacylated compound 5a was also obtained in 34% yield when the product mixture from a sodium ethoxide/ethyl acetoacetate addition containing 4a was purified by chromatography on silica gel.

Isolation of 5a was rationalised by initial nucleophilic addition of the enolate of ethyl acetoacetate to 1a, followed by a retro Claisen-type cleavage of the acetyl group (either in the reaction mixture or during the work-up) generating an extensively resonance stabilised enolate, which on protonation yielded the deacylated product 5a (Scheme 6).

**Scheme 6**

**Less stabilised enolates**

As the β-substitution of the β-chloroacrylamides with carbon based nucleophiles stabilised by two electron-withdrawing groups had proven successful, investigation of the reaction with the less stabilised enolate/enol of cyclohexanone was studied under basic and acidic conditions.

Addition of a solution of the β-chloroacrylamide 1a in THF to a solution of cyclohexanone enolate in THF (prepared by treatment of 1.1 equivalents of cyclohexanone with 1.1 equivalents of LDA in THF at 0 °C) afforded the cyclohexanoylacrylamide 6a as the major product, as a single isomer, following stirring at 0 °C for 10 minutes and chromatographic purification (Scheme 7). The presence of the β-hydrogen doublet at δH 7.73 coupled to the α-hydrogen on the cyclohexanone, which
was evident as a multiplet at $\delta_H$ 3.73-3.89, confirmed the formation of 6a. The stereochemistry of 6a was tentatively assigned as Z, but was not confirmed.

Scheme 7

While the yield is modest (51%), this result confirms that more reactive enolates can be successfully employed in the $\beta$-substitution process. Varying the reaction conditions by decreasing the temperature and increasing the number of equivalents of the cyclohexanone enolate did not lead to improved yields. The substitution of 1a was also attempted under acidic conditions by reaction of the trimethylsilyl enol ether of cyclohexanone with either a Lewis acid or fluoride ion; the starting material 1a was isolated unchanged from these conditions.

Organocuprates

Encouraged by successful reaction with the cyclohexanone enolate, reaction of organocuprates with $\beta$-chloroacrylamides was next explored.\textsuperscript{21,22} The reactivity of the $\beta$-chloroacrylamides 1a, 1c–1g towards $n$-Bu$_2$CuLi (generated using the conditions described by Dieter)\textsuperscript{23} was explored initially (Table 2).

Table 2 Michael Addition of $n$-Bu$_2$CuLi to $\beta$-Chloroacrylamides

<table>
<thead>
<tr>
<th>R$^1$</th>
<th>R$^2$</th>
<th>R$^3$</th>
<th>Product</th>
<th>2 eq. $n$-Bu$_2$CuLi, Et$_2$O, −78° to 20°, 30 min - 210 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>$\text{NR}^1\text{R}^2$</td>
<td>PhS</td>
<td>7</td>
<td>7a, 8a, 9a</td>
</tr>
<tr>
<td>Cl</td>
<td>$\text{NR}^1\text{R}^2$</td>
<td>PhS</td>
<td>8</td>
<td>7b, 8b, 9b</td>
</tr>
<tr>
<td>Cl</td>
<td>$\text{NR}^1\text{R}^2$</td>
<td>PhS</td>
<td>9</td>
<td>7c, 8c, 9c</td>
</tr>
<tr>
<td>R$^1$ = Td, R$^2$ = H, R$^3$ = H</td>
<td>1a</td>
<td></td>
<td>7a</td>
<td></td>
</tr>
<tr>
<td>R$^1$ = 6n, R$^2$ = H, R$^3$ = H</td>
<td>1c</td>
<td></td>
<td>7b</td>
<td></td>
</tr>
<tr>
<td>R$^1$ = Me, R$^2$ = Me, R$^3$ = H</td>
<td>1d</td>
<td></td>
<td>7c</td>
<td></td>
</tr>
<tr>
<td>R$^1$ = Et, R$^2$ = H, R$^3$ = H</td>
<td>1e</td>
<td></td>
<td>7d</td>
<td></td>
</tr>
<tr>
<td>R$^1$ = $\text{Pr}$, R$^2$ = H, R$^3$ = H</td>
<td>1f</td>
<td></td>
<td>7e</td>
<td></td>
</tr>
<tr>
<td>R$^1$ = Td, R$^2$ = H, R$^3$ = Me</td>
<td>1g</td>
<td></td>
<td>7f</td>
<td></td>
</tr>
</tbody>
</table>
Reaction of the β-chloroacrylamides with n-butyl cuprate led to a complex mixture of products, with the mono-substituted product the major product isolated as a mixture of E and Z isomers in most cases (entries 2–5, Table 2). The major isomer is believed to be the Z isomer. Once again the β-H signal in the $^1$H NMR spectra is characteristic of the stereochemistry, with the major isomer appearing at lower field ($\delta_H \sim 7.66$ ppm c.f. $\delta_H \sim 6.66$ ppm), reflecting a distortion from planarity in the more sterically hindered E isomer. The side-products formed included the desulfurised product (entries 1–3, Table 2) and the di-addition product (entries 1, 4–5, Table 2). The methodology was also successfully applied to the extended acrylamide 1g, with the mono-substituted product 7g isolated as a single isomer, tentatively assigned as Z (entry 6, Table 2).

The recovery of the desulfinylated products 8a, 8c and 8d and diphenyldisulfide demonstrates the relatively labile character of the carbon-sulfur bond. In order to determine if the loss of the sulfide group occurs prior to or after substitution of the β-chloroacrylamides by the organocuprates, a sample of the adduct 7c was exposed to the reaction conditions; a mixture of the adduct 7c and the di-adduct 9c was recovered, with no evidence by $^1$H NMR analysis for the presence of the desulfinylated product 8c. It thus seems likely that C-S bond cleavage occurs earlier in the reaction sequence.
As some success had been achieved for the \( n \)-butyl cuprate additions, the reaction of the methyl cuprate with \( \beta \)-chloroacrylamides was next attempted. A \( \text{Me}_2\text{CuLi} \) solution was prepared using a 2:1 ratio of methyl lithium and copper iodide in ether at \(-78^\circ\text{C}\), and this mixture was subsequently added to a solution of the \( \beta \)-chloroacrylamide in ether at \(-78^\circ\text{C}\). Table 3 summarises the results of these investigations. The reaction proved to be much cleaner than the \( n \)-butyl cuprate additions, with no evidence for the formation of other side-products, albeit with modest yields.

Table 3 Reaction of \( \text{Me}_2\text{CuLi} \) with \( \beta \)-Chloroacrylamides

<table>
<thead>
<tr>
<th>Entry</th>
<th>( \beta )-Cl</th>
<th>( R^1 )</th>
<th>( R^2 )</th>
<th>Product</th>
<th>% Yield\textsuperscript{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>Tol</td>
<td>H</td>
<td>10a\textsuperscript{b}</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>1b</td>
<td>(S)-CH(CH(_3))Ph</td>
<td>H</td>
<td>10b\textsuperscript{b}</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>1c</td>
<td>Bn</td>
<td>H</td>
<td>10c\textsuperscript{b}</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>1d-Z</td>
<td>Me</td>
<td>Me</td>
<td>10d\textsuperscript{c}</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>1d-E</td>
<td>Me</td>
<td>Me</td>
<td>10d\textsuperscript{d}</td>
<td>71</td>
</tr>
<tr>
<td>6</td>
<td>1e</td>
<td>Et</td>
<td>H</td>
<td>10e\textsuperscript{b}</td>
<td>34</td>
</tr>
<tr>
<td>7</td>
<td>1f</td>
<td>iPr</td>
<td>H</td>
<td>10f\textsuperscript{b}</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>1h</td>
<td>Allyl</td>
<td>H</td>
<td>10h\textsuperscript{c}</td>
<td>42</td>
</tr>
<tr>
<td>9</td>
<td>1i</td>
<td>nBu</td>
<td>H</td>
<td>10i\textsuperscript{b}</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>1j</td>
<td>Me</td>
<td>H</td>
<td>10j\textsuperscript{b}</td>
<td>29</td>
</tr>
<tr>
<td>11</td>
<td>1k</td>
<td>H</td>
<td>H</td>
<td>10k\textsuperscript{f}</td>
<td>39</td>
</tr>
</tbody>
</table>

\textsuperscript{a) Isolated yield after chromatographic purification}
\textsuperscript{b) Trace amount of the E isomer detected by \(^1\text{H} \) NMR spectroscopy.}
\textsuperscript{c) Isolated as an inseparable mixture of \( Z \) and \( E \) isomers of 10d in a ratio of 4:1 following chromatography. This ratio changed to 1:1 after 3 weeks.}
d) Isolated as an inseparable mixture of Z and E isomers of 10d in a ratio of of 3:8 initially and a ratio of 1.1:1 following chromatography. This ratio changed to 1.4:1 after 2 days.

e) Crude ratio of 10h-Z : 10h-E 1: 0.1. Ratio after chromatographic purification was 10h-Z : 10h-E 1: 0.05.

f) The E isomer was not detected by $^1$H NMR spectroscopy.

The addition products 10a–10j were isolated as a mixture of E and Z isomers, with the major isomer tentatively assigned as Z, while the E isomer was not detected by $^1$H NMR spectroscopy for 10k. Reaction of two equivalents of Me$_2$CuLi with one equivalent of the tertiary β-chloroacrylamide Z-1d proved interesting (entry 4, Table 3). Following chromatographic purification, the adduct 10d was isolated as an inseparable mixture of the Z and E isomers in a ratio of 4:1. When a $^1$H NMR spectrum of 10d (which had been stored at room temperature) was recorded 3 weeks later, the Z : E ratio had changed to 1 : 1. On repeating the reaction with the E isomer of 1d, a similar result was observed. The initial ratio of Z : E of 10d was 3 : 8 and following chromatography the ratio had changed to 1.1 : 1 (Z:E). After storage for 2 days at room temperature, the Z : E ratio had changed to 1.4 : 1. Evidently, the E and Z isomers of 10d can interconvert slowly. In contrast, there was no evidence for isomerisation of the corresponding n-butyl adducts 7d.

The addition of an aryl group to the β-chloroacrylamides was investigated next. It was anticipated that addition of Ph$_2$CuLi [prepared by reacting two equivalents of phenyl lithium with one equivalent of copper(I) iodide in ether at $-78$ °C] to the β-chloroacrylamides would afford the corresponding β-phenylacrylamides. However, following the work-up, the alkynamides 11a–11c were isolated (Table 4). Significantly, analogous products were never detected using the alkyl cuprates.

*Table 4 Reaction of Ph$_2$CuLi with the β-Chloroacrylamides*

<table>
<thead>
<tr>
<th>β-Cl</th>
<th>R</th>
<th>Product</th>
<th>% Yield $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Tol</td>
<td>11a</td>
<td>31</td>
</tr>
<tr>
<td>1c</td>
<td>Bn</td>
<td>11c</td>
<td>83</td>
</tr>
<tr>
<td>1f</td>
<td>iPr</td>
<td>11f</td>
<td>77</td>
</tr>
</tbody>
</table>
a) Isolated yield after chromatographic purification.

Elimination of thiophenol occurs under the basic reaction conditions (Scheme 8), possibly due to the increased acidity of the β-H, activated by the adjacent phenyl group, relative to the analogous n-butyl (7a–7g) or methyl adducts (10a–10k).

![Scheme 8](image)

The alkynamides 11a and 11c are known compounds, and are intermediates in the synthesis of 2,5-diarylisothiazolones 12a and 12c (Scheme 9), inhibitors of cytokine induced cartilage destruction.\(^\text{24}\)

![Scheme 9](image)

The reaction of the β-chloroacrylamide 1c with organocuprates derived from Grignard reagents was also explored; a number of commercially available Grignard reagents (RMgX) were used to generate organocuprates by reaction with copper(I) iodide, with starting material isolated on employment of MeMgBr/CuI, PhMgBr/CuI and iPrMgBr/CuI. The best result was achieved using iPr\(_2\)CuMgCl, affording a 1.13 : 1 ratio of starting material 1c to the adduct 13c (Scheme 10). The adduct 13c was predominantly one product, presumably Z, with a trace amount of a minor isomer. It is clear that the nature of the halide has a significant influence on the reaction.

![Scheme 10](image)
Thus, substitution at the β-position is possible using carbon nucleophiles ranging from reactive systems to stabilised enolates. The yields are modest, but they proceed with good retention of stereochemistry, and generally the mono-substituted adducts can be isolated. The overall transformation from the α-phenylthioamides to the carbon adducts reflects C-C bond formation at an originally unactivated methyl group, and is therefore synthetically useful (Scheme 11).

\[
\begin{align*}
\text{PhS} & \overset{\text{O}}{\text{O}} \text{NHR} & \overset{\text{NCS}}{\rightarrow} & \text{PhS} & \overset{\text{O}}{\text{O}} \text{NHR} & \overset{\text{Cl}}{\rightarrow} & \text{PhS} & \overset{\text{O}}{\text{O}} \text{NHR} \\
\quad & \quad & & R^1 & \overset{\text{C}}{\text{C}} & R^3 & R^1 & \overset{\text{C}}{\text{C}} & R^3 \\
\end{align*}
\]

*Scheme 11*

**Nitrogen Nucleophiles**

Introduction of nitrogen atoms to a carbon framework is particularly important in the synthesis of biologically active molecules such as amino acids, β-amino acids or alkaloids.\(^{25,26}\) Amines are excellent nucleophiles, reacting readily with even poorly electrophilic species.\(^ {27}\)

The reaction of primary or secondary amines with β-chloroacrylamides was envisaged to follow the pathway outlined in Scheme 12 to generate enaminoamide derivatives. Nucleophilic addition at the β-carbon followed by elimination of chloride would produce enaminoamides which are stabilised by extensive resonance delocalisation. Indeed, rapid interconversion of the *E* and *Z* isomers is envisaged in these systems, in contrast to all other derivatives investigated during this work, due to the extended conjugation. The addition of a second equivalent of amine should be disfavoured as delocalisation of the nitrogen lone pair significantly reduces the electrophilicity of the β-carbon.

\[
\begin{align*}
\overset{\text{Cl}}{\text{R}^3} \overset{\text{O}}{\text{O}} & \overset{\text{NR}^1\text{R}^2}{\text{Cl}} \overset{\text{NH}^*\text{R}^6}{\rightarrow} & \overset{\text{R}^3\text{R}^4\text{N}}{\text{O}} \overset{\text{NR}^1\text{R}^2}{\rightarrow} & \overset{\text{R}^3\text{R}^4\text{N}}{\text{O}} \overset{\text{NR}^1\text{R}^2}{\rightarrow} \\
\quad & \quad & & \quad & \quad \\
\end{align*}
\]

*Scheme 12*
The reaction of β-chloroacrylamides with amines to produce β-enaminoamides was initially explored using the secondary amines dimethyl-, diethyl- and diisopropylamine and morpholine. Table 5 summarises the results of these experiments.

**Table 5 Addition of Secondary Amines to the β-Chloroacrylamides**

<table>
<thead>
<tr>
<th>Entry</th>
<th>β-Cl</th>
<th>R</th>
<th>R’</th>
<th>R’’</th>
<th>R’’’</th>
<th>Product</th>
<th>Time (h)</th>
<th>% Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>Me</td>
<td>Ph</td>
<td>Tol</td>
<td>H</td>
<td>H</td>
<td>14a’</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>1v</td>
<td>Me</td>
<td>Bn</td>
<td>Bn</td>
<td>H</td>
<td>H</td>
<td>14v’</td>
<td>0.25</td>
</tr>
<tr>
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<td>1a</td>
<td>Et</td>
<td>Ph</td>
<td>Tol</td>
<td>H</td>
<td>H</td>
<td>15a’</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>1v</td>
<td>Et</td>
<td>Bn</td>
<td>Bn</td>
<td>H</td>
<td>H</td>
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<td>H</td>
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<td>Bn</td>
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<td>17o’</td>
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<td>Bn</td>
<td>Tol</td>
<td>H</td>
<td>H</td>
<td>17q’</td>
<td>0.5</td>
</tr>
</tbody>
</table>

a) A solution of the amine in ethanol was added to the β-chloroacrylamide.
b) Isolated yield after recrystallisation.
c) Crude yield, further purification was not required.
d) The β-chloroacrylamide was added to neat DIPA.
e) 2.5 equivalents of morpholine were added to a dichloromethane solution of the β-chloroacrylamide.
f) 5 equivalents of morpholine were required for completion of reaction.
g) Isolated yield after triturating from ether and hexane
h) Isolated as a 1:1.3 mixture of the E and Z isomers of 17l.
i) Isolated as a 1:2:1 mixture of the E and Z isomers of 17l.
j) Isolated as a 4:1 mixture of the E and Z isomers of 17m.
k) Isolated as a 1:10 mixture of the E and Z isomers of 17n.
l) Isolated yield after chromatographic purification.

The β-chloroacrylamides 1a and 1v were added to an ethanolic solution of dimethylamine and diethylamine, and the β-chloroacrylamide 1a was added to neat diisopropylamine; the resulting solutions were then stirred at room temperature. The
reaction progress was monitored by TLC analysis and very efficient substitution of the chloride by the amines was observed (entries 1–5, Table 5). An excess of the amine was employed due to amine salt formation with the HCl released in the substitution. Significantly, only one isomer of the enaminoamides 14a, 14v, 15a, 15v and 16a was evident by $^1$H NMR spectroscopy in each of the transformations. The slower conversion of 1a when treated with DIPA reflects the poorer nucleophilicity of this amine, although it is notable that the addition of DIPA proceeded very efficiently under these mild conditions. Although the enaminoamides 14a and 15a were purified by recrystallisation, in general the crude products were found to be of sufficient purity to use in subsequent reactions.

The treatment of 1a with morpholine was particularly efficient, resulting in rapid and clean transformation to the Z-β-morpholinoacrylamide 17a. The effect on the morpholine substitution of variation in the amide and sulfide substitutents was then investigated (entries 6–15, Table 5). In most instances, the β-morpholinoacrylamides were analytically pure and no purification was required. For the primary and secondary β-chloropropenamides, the morpholine adducts were isolated as the Z-isomers exclusively (entries 6—8 and 13–15, Table 5), while employment of the tertiary and extended chain acrylamides led to a mixture of $E$ and $Z$ isomers (entries 9–11, Table 5). The tertiary and extended chain acrylamides required much longer reaction times (entries 7, 9–12, Table 5), presumably due to steric (for the extended chain acrylamides) and conformational effects (for the tertiary acrylamides). In order to determine if the stereochemistry of the β-chloroacrylamides influenced the efficiency and/or stereochemical outcome of the reaction, the $Z$ and $E$ isomers of the β-chloropentenamide 1l were reacted separately with morpholine. It was found that $Z$-1l had completely reacted with morpholine after 22 h while $E$-1l had not been completely transformed even after 96 h. Thus, the $Z$ isomer reacts much more efficiently in nucleophilic substitutions. This is also reflected in the longer reaction times required for the reaction of $E$-1d than $Z$-1n (entries 7 and 12, Table 5).

The observation of only one enaminoamide isomer on treatment of 1a and 1v with the secondary amines dimethylamine and diethylamine, on treatment of 1a with diisopropylamine and of 1a, 1d, 1f and 1o−1q with morpholine is significant. When a
secondary amine reacts with a \( \beta \)-chloroacrylamide, two conformational changes leading to chloride loss can be envisaged. Kinetically, formation of the Z isomer via A is favoured due to unfavourable steric interactions in B (Figure 1). However, extensive resonance delocalisation in the enaminoamides is expected to allow rapid interconversion between the \( E \) and \( Z \) isomers and therefore it is believed that the thermodynamically determined ratio is observed. For the enaminoamides 14a, 14v, 15a, 15v, 16a, 17a, 17d, 17f and 17o–17q the \( Z \) isomer is strongly favoured, and indeed in practice the \( E \) isomer cannot be detected by \(^1\)H NMR spectroscopic analysis.

![Figure 1](image1.png)

With the extended chain \( \beta \)-chloroacrylamides 11 and 1m, formation of two isomers of the enaminoamides is observed, reflecting a decrease in the energy difference between the two isomers (Scheme 13). Similarly, with the tertiary propenamide \( Z \)-1n, formation of both \( E \) and \( Z \) isomers of the morpholine adduct is observed, albeit with the \( Z \) isomer dominating (\( E:Z \) 1:10). The different conformational properties of the tertiary amides have been previously observed to affect the stereochemical outcome due to the absence of the intramolecular hydrogen bond, for example in the chlorination reaction.\(^{15}\)

![Scheme 13](image2.png)
Evidence for the delocalisation of the nitrogen lone-pair was seen in the \(^1\)H and \(^{13}\)C NMR spectra of enaminoamides 14a, 15a and 16a. For example, in the \(^1\)H NMR spectrum of the dimethylamino adduct 14a, the signal for the methyl groups (δ\(_\text{H}\) 3.35-3.65) was shifted considerably downfield compared to the amine (δ\(_\text{H}\) 2.42). In addition, the signal was broadened due to restricted rotation; both features indicate extensive delocalisation of the nitrogen lone-pair into the conjugated system. Also, in the \(^{13}\)C NMR spectrum, a broad signal was evident for the methyl groups at δ\(_C\) 42.7.

In the \(^1\)H NMR spectrum of the \(E\) and \(Z\) isomers of the \(N\)-tolyl-\(\beta\)-morpholinopentenamide 17m, signals due to the morpholino substituent of the minor isomer \(Z\)-17m were present at δ\(_\text{H}\) 3.40-3.43, while the corresponding signals for the major isomer \(E\)-17m were evident at δ\(_\text{H}\) 2.85-2.89. As the latter signals are very similar to the chemical shifts of the methylene hydrogens in free morpholine (which are seen at δ\(_\text{H}\) 2.85-2.91), it is evident that the extent of delocalisation of the nitrogen lone pair into the conjugated system in the \(E\) isomer is much less than in the \(Z\) isomer. Examination of the structures illustrated in Figure 2 indicates that 1,3-allylic strain in the \(E\) isomer would result in more ‘out of plane’ rotation of the morpholine substituent, leading to poor overlap of the nitrogen lone-pair with the π-orbitals of the conjugated system.

The reactivity of a range of sulfoxide derivatives of the \(\beta\)-chloroacrylamides with the secondary amines diethylamine, diisopropylamine, piperidine and morpholine was also studied, with the stereochemical outcome dependant on the nature of the amine and sulfoxide employed (Table 6).

Table 6 Addition of Secondary Amines to the Sulfoxides
As observed with the sulfides, the sulfoxides 18a–18g proved to be very efficient Michael acceptors with the secondary amines as nucleophiles, and the reactions were generally complete within 5 minutes by TLC analysis. In each instance, the enamino adducts were isolated as an inseparable mixture of E and Z isomers, in contrast to the results with the sulfide series. The isomers were distinguished by the position of the β-hydrogen signals; the β-hydrogen signal of the E isomer is typically 1 ppm upfield from the corresponding signal in the Z isomer.
On employment of diisopropylamine and diethylamine as nucleophiles the Z isomer of the sulfoxide adduct is favoured (entries 1–4, Table 6), due to steric interactions of the amino substituent with the amide group in the E isomer (Scheme 14).

![Scheme 14](image)

Interestingly, on reaction of dimethylamine, the E isomer is the major isomer obtained for the benzenesulfinyl adduct 21a, while the Z isomer is favoured for the more conformationally flexible benzylsulfinyl adduct 21g. Reaction of the conformationally constrained secondary amines piperidine and morpholine resulted in the E isomer predominating in most cases (entries 7–14, Table 6). Due to the intramolecular hydrogen bond between the oxygen of the sulfoxide and the amide proton, the sulfoxide adduct is held in a very rigid conformation, resulting in a significant interaction between the amino substituent and the sulfoxide in the Z isomer and the amide substituent in the E isomer. When piperidine is used as the nucleophile, the E isomer is favoured for both the benzenesulfinyl adduct 22a and the methylsulfinyl adduct 22b, although to a greater extent for the benzenesulfinyl adduct (entries 7 and 8, Table 6).

Addition of morpholine to the sulfoxides led to some very interesting trends; on employment of the benzenesulfinyl derivatives 18a and 18c, the E isomer is preferred (entries 9 and 11, Table 6). On changing to the methylsulfinyl derivative 18b, an equimolar mixture of E and Z isomers are formed due to reduced steric interaction between the smaller methyl group and the morpholino substituent (entry 10, Table 6). The introduction of the more conformationally flexible benzyl group at the sulfur centre leads to the Z isomer as the major isomer, as the benzyl group can accommodate the morpholino substituent more readily (entries 12–14, Table 6).

The addition of morpholine to a range of sulfone derivatives was also investigated, with the results summarised in Table 7.16
The synthesis of the sulfone adducts 24a, 24d–24m has already been described, where the morpholino adducts were employed to enable characterisation of the more labile β-chlorosulfones.16 In each instance the $E$ isomer was formed exclusively, confirmed by single crystal X-ray diffraction on a sample of 24a recrystallised from dichloromethane/hexane (See supporting information). Clearly, the introduction of a second oxygen atom at the sulfur centre increases the steric demand at this centre, pushing the equilibrium completely towards the $E$ isomer (Figure 3).
The crystal structure reveals the existence of a hydrogen bond from the amide proton to an oxygen of the sulfone, leading to a highly organised and rigid six-membered structure. Interestingly, the acrylamide unit is quite distorted from planarity, reflecting limited conjugation between nitrogen and the acrylamide system.

Comparing the morpholine adducts at the sulfide, sulfoxide and sulfone levels of oxidation leads to some interesting trends. For the sulfide adducts 17a–17i (Table 5), steric interaction between the morpholino group and the carbonyl group of the amide in the E-isomer results in the exclusive formation of the Z-isomer in all instances. For the sulfoxide adducts 23a–23f, a mixture of E- and Z-isomers are obtained, with the Z-isomer the major isomer for the benzylsulfinyl adducts 23d–23f (Table 6). Clearly, the introduction of the oxygen atom at the sulfur centre together with the alteration to a six-membered hydrogen bonded system leads to increased steric hindrance in the Z-isomer between the morpholino group and the benzyl substituent. Therefore, the conformational mobility in the six-membered hydrogen bonded system involving oxygen is significantly less than in the five-membered hydrogen bonded system involving sulfur. However, the interaction between the morpholino group and the amide carbonyl in the E-isomer is more sterically demanding, and thus the Z-isomer is the major isomer obtained. Interestingly, in the addition of morpholine to benzenesulfinyl derivatives, the E-isomer was the major isomer obtained, and employment of methylsulfinyl derivatives led to an equimolar mixture of the E- and Z-isomers. For the benzenesulfinyl derived adducts, the interaction between the phenyl group attached to the sulfur centre and the morpholino substituent is significant and pushes the equilibrium in the direction of the E-isomer. Employment of the smaller methyl group reduces the steric interaction with the morpholino substituent leading to a 1:1 mixture of the E- and Z-isomers. Introduction of the more conformationally flexible benzyl group at the sulfur centre leads to the Z-isomer as the major isomer, presumably as the benzyl group can adjust to accommodate the morpholino substituent more easily than an S-aryl group. It is interesting to note that formation of the Z-isomer is slightly more favourable in the S-benzyl derivatives than in the S-methyl derivatives, although energetically the difference is very small. Thus, in
addition to a steric effect, it is likely that there is also a more subtle electronic effect operating. Finally, the introduction of a second oxygen atom at the sulfur centre increases the steric interaction in the Z-isomer, and the E-isomer is formed essentially exclusively at the sulfone level of oxidation. Thus, the steric demand of the sulfur substituent increases gradually from the sulfide (Z-isomer exclusively) to the sulfoxide (mixture of Z- and E-isomers) to the sulfone (E-isomer exclusively) (Scheme 15).

Scheme 15

Nucleophilic addition by primary amines to the sulfides and sulfoxides was next explored (Table 8). Once again, efficient nucleophilic substitution took place with the primary amines, and as highly conjugated enaminoamides are formed, there is no evidence for the second addition of a nucleophile. Interestingly, each of the products existed exclusively as the enamino tautomers, with no evidence for the corresponding imine tautomers.

Table 8 Addition of Primary Amines to β-Chloroacrylamides

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<tr>
<th>Entry</th>
<th>β-Cl</th>
<th>n</th>
<th>R</th>
<th>R¹</th>
<th>Product</th>
<th>Z:Eᵃ</th>
<th>% Yieldᵇ</th>
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<td>0</td>
<td>Me</td>
<td>Tol</td>
<td>25a</td>
<td>1:3ᵉ</td>
<td>Quant.d</td>
</tr>
<tr>
<td>2</td>
<td>1b</td>
<td>0</td>
<td>CH(CH₃)Ph</td>
<td>(S)-CH(CH₃)Ph</td>
<td>26b</td>
<td>1:3</td>
<td>57</td>
</tr>
<tr>
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<td>18a</td>
<td>1</td>
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<td>Tol</td>
<td>27a</td>
<td>E only</td>
<td>60</td>
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<td>4</td>
<td>18c</td>
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<td>93</td>
</tr>
<tr>
<td>5</td>
<td>18a</td>
<td>1</td>
<td>iPr</td>
<td>Tol</td>
<td>28a</td>
<td>E only</td>
<td>81</td>
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</table>

ᵃ) Determined by integration of the β-hydrogen signal for each isomer in the ¹H NMR spectrum.
b) Isolated yield after chromatographic purification unless otherwise stated.
c) The E and Z isomers were found to interconvert on silica gel or on storage at room temperature.
d) Crude yield.
The primary amine was added neat to a dichloromethane solution of the sulfide or sulfoxide, and the reactions were complete within 5 minutes. The stereochemical outcome was dependant upon the oxidation level at the sulfur centre.

Addition of methylamine to the sulfide 1a afforded the adduct 25a as a 3:1 mixture of the E and Z isomers which slowly interconverted on silica gel or on storage at room temperature, confirmed by two-dimensional TLC analysis. Partial separation of the isomers was possible by chromatography on silica gel. The characteristic signals of the enamine proton and the β-hydrogen in the ^1H NMR spectrum are depicted in Figure 4.

Assignment of the relative stereochemistry was based on the downfield shift of the enamine proton in the E isomer; the enamine proton for the less polar E isomer was evident at δ_H 9.03-9.20, while the enamine proton for the more polar Z isomer was present at δ_H 5.40-5.60. Again, the signal for the β-hydrogen of the Z isomer appeared further downfield at δ_H 8.22 than the corresponding signal in the E isomer, which lay within the aromatic region (δ_H 7.04-7.41). This assignment is consistent with the polarity, where E-25a is less polar, having more extensive intramolecular hydrogen-bonding.

The chiral sulfide 1b was treated with a racemic mixture of α-methylbenzylamine to yield a 3:1 mixture of the E and Z isomers of 26b, each as a mixture of two diastereomers. As the E and Z isomers interconverted on silica they were not isolable separately. Though the ratio of the E and Z isomers was 3:1, the difference between the amounts of diastereomers of each geometrical isomer was negligible. The chiral amide auxiliary is too remote to influence the selectivity of the attack at the β-carbon.
Significantly, the stereochemistry and particularly the number of intramolecular hydrogen bonds in the $E$ and $Z$ isomers influence the physical properties of the compounds. Not only do they have different polarities on silica gel ($R_f$ values were 0.5 apart in both $25a$-$E/Z$ and $26b$-$E/Z$), their solubilities in the same solvent differ substantially. The $E$ isomers of both $25a$ and $26b$ are eluted with ethyl acetate-hexane (25:75), while the more polar $Z$ isomers require the addition of ethanol (for $25a$) or dichloromethane (for $26b$) to the eluent for elution from silica gel.

Interestingly, addition of methylamine and isopropylamine to the sulfoxides afforded the adducts $27a$, $27c$ and $28a$ as single stereoisomers, assigned as $E$ by comparison of the $^1H$ NMR spectroscopic data with that of the sulfide adducts $25a$ and $26b$ (see for example Figure 5).

Thus, in the sulfoxide the $E$ isomer, stabilised by two intramolecular hydrogen bonds, is significantly more stable than the $Z$ isomer. In contrast, at the sulfide level of oxidation, both the $E$ and $Z$ isomers are observed, indicating that the decreased steric interactions in the $Z$ isomer compensate for the loss of enamine to carbonyl hydrogen bond in the $E$ isomer. The steric constraints in the sulfoxide are clearly greater than that in the sulfide, even though both are hydrogen bonded to the amide (Scheme 16).
Finally, treatment of the sulfide 1a with ammonia and hydroxylamine results in chloride substitution analogous to the reaction with amines, but in these instances resulted in relatively complex mixtures of products due to the potential for both $E$ and $Z$ isomer formation and imine-amine tautomerisation (see Supporting Information).

Thus, primary and secondary amines act as very effective nucleophiles leading to single nucleophilic addition and chloride substitution at the sulfide, sulfoxide and sulfone levels of oxidation. Unlike all other compounds studied during this work (i.e. $\beta$-chloroacrylamides and the carbon and oxygen based adducts), rapid equilibration between $Z$ and $E$ isomers is seen in the amine adducts, enabled by extensive resonance conjugation in enaminoamides (Scheme 12). Thus, while the $Z/E$ ratios in all the other nucleophilic substitutions appear to reflect kinetic features, with the amino adducts in general the thermodynamic ratio of $Z$ and $E$ isomers is observed. Interestingly, the ratio of these isomers can be rationalised based on the level of sulfur oxidation and the steric effect of the thio and amide substituents. Intramolecular hydrogen bonding plays a very strong role in determining the $Z/E$ ratio. In general, the enaminoamides are very stable compounds, presumably reflecting the extended conjugation, and indeed formation of these derivatives enabled characterisation of the more labile $\beta$-chlorosulfones.

**Oxygen Nucleophiles**

Reaction of alkoxides with the $\beta$-chloroacrylamides was expected to follow a similar pathway to that of the amines, although in contrast to the nitrogen-substituted acrylamides in which the $\beta$-carbon was no longer nucleophilic, it was envisaged that the $\beta$-alkoxyenamides formed by addition of alkoxide may be susceptible to a second addition of nucleophile, leading to the disubstituted product due to the strongly inductive electron withdrawing effect of the oxygen substituent, which renders the $\beta$-carbon electrophilic, despite the potential for resonance delocalisation (Scheme 17). This would lead to an interesting series of acetal derivatives.

![Scheme 17](image-url)
Exploratory experiments involved treating a sample of 1a with two equivalents of freshly prepared sodium ethoxide or methoxide in ethanol or methanol. Treatment of 1a with two equivalents of sodium methoxide gave a mixture of two products within 30 min; both the β-methoxyacrylamide 33a and the β,β-dimethoxypropanamide 34a were isolated in a 1:5 ratio after aqueous workup. Similarly, treatment of 1a with two equivalents of sodium ethoxide gave a mixture of β-ethoxyacrylamide 35a and β,β-diethoxypropanamide 36a, but in a ratio of 1:1.5. The reaction of the benzylthio β-chloroacrylamide 1v with two equivalents of sodium methoxide and sodium ethoxide was also investigated. A mixture of the β-methoxyacrylamide 33v and the β,β-dimethoxypropanamide 34v was obtained in a ratio of 1:1.8 on reaction with sodium methoxide, while the β-ethoxyacrylamide 35v and the β,β-diethoxypropanamide 36v were obtained in a ratio of 1:1.2 on reaction with sodium ethoxide (Scheme 18).

As the dimethoxyamides were of interest from a synthetic perspective, the conditions for their formation were optimised and it was found that use of 2.1 equivalents of sodium methoxide in methanol at room temperature resulted in clean transformation of the β-chloroacrylamides to the acetals. The scope of the transformation to the acetal was established as summarised in Table 9.

Table 9 Formation of β,β-Dimethoxyamides
In all cases, transformation to the acetal was achieved in good yield. In most instances, the products were found to be of sufficient purity to use in subsequent transformations without further purification. The secondary propanamides reacted efficiently within 1 hour (entries 1–3, 5, Table 9), while the primary, tertiary and extended amides necessitated longer reaction times (entries 4, 6 and 7, Table 9).

Due to the absence of the intramolecular hydrogen bond, the conformational features of the tertiary amide derivative 34n differed from those of the corresponding secondary amides 34a, 34b, 34f, 34k, 34n, 34r. Thus, the $^{3}J$ coupling between the $\beta$-hydrogen and the $\alpha$-hydrogen in 34a, 34b, 34f, 34k, 34n, 34r is typically 4 Hz, while in the tertiary amide 34n an 8 Hz coupling is observed.

The formation of the dimethoxyamide derivatives of the sulfoxides was also explored. Table 10 summarises the results of these experiments.

### Table 10 Formation of $\alpha$-Sulfinyl-$\beta,\beta'$-Dimethoxyacrylamides

<table>
<thead>
<tr>
<th>Entry</th>
<th>Sulfoxide</th>
<th>$R$</th>
<th>$R'$</th>
<th>$R''$</th>
<th>Acetal</th>
<th>d.r.$^a$</th>
<th>% Yield$^b$</th>
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<tbody>
<tr>
<td>1</td>
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<td>Me</td>
<td>Ph</td>
<td>Tol</td>
<td>37a</td>
<td>1.8:1</td>
<td>56 + 27$^c$</td>
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<tr>
<td></td>
<td>18g</td>
<td>Me</td>
<td>Bn</td>
<td>Bn</td>
<td>37g</td>
<td>6.6:1</td>
<td>42 + 11c</td>
</tr>
<tr>
<td>---</td>
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<td>-------</td>
<td>---------</td>
</tr>
<tr>
<td>3</td>
<td>18a</td>
<td>Et</td>
<td>Ph</td>
<td>Tol</td>
<td>38a</td>
<td>2.0:1</td>
<td>44 + 20c</td>
</tr>
<tr>
<td>4</td>
<td>18g</td>
<td>Et</td>
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<td>Bn</td>
<td>38g</td>
<td>1.1:1</td>
<td>90d</td>
</tr>
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</table>

a) d.r. = diastereomeric ratio of the crude product by $^1$H NMR spectroscopy.
b) Yield after chromatographic purification
c) A pure sample of the major isomer was obtained by column chromatography. The minor isomer was contaminated with the major isomer in each instance.
d) Isolated as a mixture of the major and minor diastereomers.

Treatment of the sulfoxides 18a and 18g with 2.1 equivalents of sodium methoxide led to a mixture of two diastereomers of the corresponding dimethoxyacrylamides 37a and 37g (entries 1 and 2, Table 10). It was possible to obtain a pure sample of the major isomer of 37g by chromatography on silica gel. Similarly, reaction of 18a and 18g with 2.1 equivalents of sodium ethoxide led to a diastereomeric mixture of the diethoxyacrylamides 38a and 38g (entries 3 and 4, Table 10). The relative stereochemistry of the major isomer of the acetal 38a was determined by single crystal X-ray diffraction after recrystallisation of a sample from acetonitrile/acetone (See Supplementary Information).

While the acetals are readily accessed, in general for alkoxide additions to multiple bonds, monoaddition is difficult to control.29-32 However, as the β-methoxypropenoate and propenamide units are very important for the fungicidal activity of several agrochemicals,33-36 the monoaddition of methoxide anion to the β-chloroacrylamides was investigated in more detail. A number of experiments were conducted on the β-chloroacrylamide 1a, in which the effect of solvent, temperature, counterion and base were investigated. The optimum conditions for monoaddition were found to be addition of 1.4 equivalents of lithium methoxide (generated from n-butyllithium in methanol) to a solution of 1a in THF at −78 °C, and the reaction mixture was then allowed to warm slowly over 3 hours to −5 °C. On employment of these conditions, the monoaddition product 33a and the acetal 34a were produced in a 9:1 ratio respectively, with no other side-products detected. The formation of the acetal could never be completely avoided. The scope of the monoaddition was then investigated by employment of various sulfide, amide and β-alkyl substituents on the β-chloroacrylamide (Table 11).
Table 11 Reaction of β-Chloroacrylamides with Lithium Methoxide

![Diagram](image)

<table>
<thead>
<tr>
<th>β-Cl</th>
<th>R¹</th>
<th>R²</th>
<th>R³</th>
<th>R⁴</th>
<th>T⁰°C</th>
<th>Time/h</th>
<th>Product</th>
<th>% Yield (A)ᵇ</th>
<th>A:Bᶜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Ph</td>
<td>Tol</td>
<td>H</td>
<td>H</td>
<td>-5</td>
<td>3.5</td>
<td>33a</td>
<td>60</td>
<td>9:1</td>
</tr>
<tr>
<td>1gᵈ</td>
<td>Ph</td>
<td>Tol</td>
<td>H</td>
<td>Me</td>
<td>20</td>
<td>18e</td>
<td>33g 34g</td>
<td>-f</td>
<td>1:1</td>
</tr>
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<td>H</td>
<td>0</td>
<td>2</td>
<td>33h 34h</td>
<td>69</td>
<td>20:1</td>
</tr>
<tr>
<td>1nᵈ</td>
<td>Ph</td>
<td>Ph</td>
<td>Ph</td>
<td>H</td>
<td>20</td>
<td>18</td>
<td>33n 34n</td>
<td>11</td>
<td>1:2</td>
</tr>
<tr>
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<td>Tol</td>
<td>H</td>
<td>H</td>
<td>10</td>
<td>4</td>
<td>33r 34r</td>
<td>30</td>
<td>3:1</td>
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<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

a) Temperature at which the reaction was complete.
b) Isolated yield following chromatographic purification.
c) Ratio of β-methoxyacrylamide A to β,β-dimethoxyadduct B after chromatography.
d) 1:1 mixture of the E and Z isomers.
e) The reaction was incomplete on reaching room temperature and was allowed to stir at room temperature overnight.
f) Isolated as a 1:1 inseparable mixture with 34g.

The yields, reaction times and levels of purity vary considerably on variation of the sulfide, amide and β-alkyl substituents. In most instances, the monoadduct was isolated as the Z isomer exclusively. The N-tolyl- and N-allyl-β-chloroacrylamides 1a and 1h gave the monoaddition products 33a and 33h in yields of 60% and 69% respectively, along with small amounts of the β,β-dimethoxypropanamides 34a and 34h. Changing the α-thio substituent from phenylthio to n-buty1thio reduces the electrophilicity of the β-carbon and in turn the efficiency of the transformation, with 33r isolated in 30% yield. Treatment of a 1:1 mixture of the E and Z isomers of the tertiary N,N-diphenyl-β-chloroacrylamide 1n with lithium methoxide gave complete transformation of the starting material only after 18 hours; the acetal 34n was the major product isolated from the reaction in 31% yield, with the monoaddition product 33n obtained in just 11% yield.
Reaction of a 1:1 mixture of the $E$ and $Z$ isomers of the butenamide 1g with lithium methoxide resulted in incomplete reaction even after stirring at room temperature overnight, presumably due to decreased rate of addition at the substituted $\beta$-carbon. The product contained an equimolar inseparable mixture of the monoadduct 33g and the acetal 34g. Interestingly, 33g was formed as a mixture of the $Z$ and $E$ isomers in a 5:1 ratio.

Thus, while formation of the $\beta$-methoxyacrylamide derivatives can be achieved, it is not possible to completely prevent competing acetal formation. As the $E$ isomer was only observed for the butenamide 33g, there is no evidence for thermodynamic equilibration in the enol ethers, in contrast to the enamino derivatives.

The reactivity of the $\beta$-chloroacrylamides towards a range of diols was also explored. On treatment of ethylene glycol with 2 equivalents of $n$-butyllithium in THF at 0 °C and subsequent addition of the $\beta$-chloroacrylamides 1a or 1c, the 1,3-dioxolanes 39a and 39c were isolated as white crystalline solids in yields of 60% and 50% respectively after chromatographic purification (Scheme 19). This offers a practical synthetic method for converting the unfunctionalised methyl group of an $\alpha$-thioamide to an acetal in two rapid, efficient and easily conducted steps.

The reaction of ethylene glycol with the sulfoxide 18a was also explored under identical conditions to those described above for the sulfide derivatives. Analagous to the reaction of the sulfoxides with the alkoxides, a mixture of two diastereomers of the 1,3-dioxolane adduct 40a was obtained in a 1.2:1 ratio (Scheme 20).
As the synthesis of 39a, 39c and 40a had proceeded so efficiently, the synthesis of acetals derived from chiral diols which could serve as chiral synthons was investigated. Chiral acetals have been widely used as auxiliaries and can be easily removed after exerting their stereocontrol.\textsuperscript{37} Chiral acetals are normally prepared under acidic conditions,\textsuperscript{38,39} whereas the acetals are prepared under basic conditions during this work.

Four C\textsubscript{2}-symmetric diols were employed; (2\textsuperscript{R},3\textsuperscript{R})-2,3-butanediol 41a, (2\textsuperscript{S}, 3\textsuperscript{S})-2,3-butanediol 41b, (2\textsuperscript{R},4\textsuperscript{R})-2,4-pentanediol 41c and (2\textsuperscript{R},3\textsuperscript{R})-diethyl tartrate 41d. Table 12 summarises the results of these investigations.

\textit{Table 12 Reaction of $\beta$-Chloroacrylamides with Chiral Diols}

<table>
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<tr>
<th>$\beta$-Cl</th>
<th>R\textsuperscript{1}</th>
<th>R\textsuperscript{2}</th>
<th>R\textsuperscript{3}</th>
<th>R\textsuperscript{4}</th>
<th>Diol</th>
<th>Product</th>
<th>% Yield\textsuperscript{a}</th>
<th>d.r.\textsuperscript{b}</th>
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<tr>
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<td>42a</td>
<td>65</td>
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<td>H</td>
<td>Tol</td>
<td>H</td>
<td>41b</td>
<td>43a</td>
<td>43</td>
<td>53:47</td>
</tr>
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<td>H</td>
<td>Tol</td>
<td>H</td>
<td>41c</td>
<td>44a</td>
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<td>50:50</td>
</tr>
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<td>H</td>
<td>Tol</td>
<td>H</td>
<td>41d</td>
<td>45a</td>
<td>66</td>
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<td>1b</td>
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<td>H</td>
<td>(S)-CH(CH\textsubscript{3})Ph</td>
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<td>41a</td>
<td>42b</td>
<td>68</td>
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<tr>
<td>1b</td>
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<td>(S)-CH(CH\textsubscript{3})Ph</td>
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<td>Ph</td>
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<td>H</td>
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<td>45n</td>
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<td>Tol</td>
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<td>42r</td>
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<td>H</td>
<td>41b</td>
<td>43s</td>
<td>20</td>
<td>50:50</td>
</tr>
</tbody>
</table>

a) Isolated yield after chromatographic purification.
b) d.r.=diastereomeric ratio following chromatographic purification.
c) 41c was isolated as a 1:2 mixture with diethyl tartrate.
d) 1:1 mixture of the E and Z isomers.

Two equivalents of n-butyllithium were added to a solution of the diol in THF at 0 °C and following stirring for ten minutes, a THF solution of the β-chloroacrylamide was added. When the 2,3-butanediols 41a and 41b and diethyl tartrate 41d were employed, the reaction was conducted at room temperature, whereas the reaction of the β-chloroacrylamides with the deprotonated 2,4-pentanediol 41c was faster and was therefore conducted at 0 °C to minimise side-product formation. Dioxolanes were produced from treatment of β-chloroacrylamides with butanediols, while dioxanes were generated from reaction with pentanediol. Purification by chromatography on silica gel was necessary for isolation of analytically pure acetals; however, the crude product in each case was essentially one compound (as a mixture of two diastereomers) by 1H NMR spectroscopy.

Analysis of the diastereomeric ratios of the purified products outlined in Table 12 show that the dioxolanes derived from the butanediols 41a and 41b and the dioxanes were formed without any significant diastereoselectivity, with the ratio of diastereomers
always close to 1:1. The dioxane 44g produced from a 1:1 mixture of the E and Z isomers of the β-chlorobutenamide 1g and the pentanediol 41c showed a modest preference for one diastereomer of the acetal (d.r. 73:27). A slight diastereomeric excess was also seen on use of diethyl tartrate 41d with 1a, 1c and 1n.

The yields were lower for the acetals derived from the n-butylthio-β-chloroacrylamides 1r and 1s, possibly reflecting enhanced electron donation from the alkylthio substituent decreasing the electrophilicity of the Michael acceptor, and for the acetals derived from the β-chlorobutenamide 1g, presumably for steric reasons.

In the reactions of the chiral β-chloroacrylamide 1b, there was no detectable difference in the diastereocntrol, indicating that the amide auxiliary has little or no impact on this.

As seen with the dimethoxyacrylamides, the coupling constants for the CHS and CH-2’ protons in the tertiary amide (7−8 Hz) is notably different to that in the secondary amides (2−4 Hz), reflecting a conformational change in the absence of the intramolecular hydrogen bond.

The scope of the alkoxide substitution reaction was then extended to include intramolecular substitution. While it proved difficult to prevent double addition with intermolecular alkoxide substitution, it was envisaged that control may be possible in an intramolecular fashion.

Treatment of the β-chloroacrylamide Z-1t with two equivalents of LiHMDS (generated in situ from HMDS and butyllithium) in THF afforded the carboxin 46a in 41% yield following stirring at room temperature for 48 hours (Scheme 21).

![Scheme 21](image)

The extension of this methodology to the E isomer of 1t led to the formation of the oxathianone 47a, with no evidence for the presence of the analogous carboxin. The oxathianone 47a is presumably formed by nucleophilic displacement of anilide by the alkoxide, followed by nucleophilic substitution of chloride by the displaced aniline. The
oxathianone was isolated as a single isomer, but the relative stereochemistry has not been confirmed (Scheme 22).

![Scheme 22](image)

Carboxins are of biological importance, as compounds of this type are active components of commercially available pesticides and fungicides (for example Vitavax\textsuperscript{®} 46b and Plantavax\textsuperscript{®} 46c).

![46b](image) ![46c](image)

The scope of this methodology was then extended to the $E$- and $Z$-$\beta$-chlorobutenamides 1u-$E/Z$; treatment of the $E$ isomer of 1u with two equivalents of LiHMDS yielded the carboxin 46b in 7% yield, while 46b was isolated in 11% yield on reaction of the $Z$ isomer of 1u (Scheme 23).

![Scheme 23](image)

Thus, the $\beta$-chloroacrylamides act as very efficient Michael acceptors in reactions with oxygen based nucleophiles. A second addition of the oxygen nucleophiles readily occurs, leading to a range of novel acetals, however it is possible to stop the reaction at the monoaddition product to yield the corresponding $\beta$-methoxypropenamides. The use of diols as nucleophiles results in very efficient cyclic acetal formation. In an intramolecular sense, monoaddition is more readily controlled, as might be expected.
**Sulfur Nucleophiles**

Analogous to oxygen based nucleophiles, sulfur based nucleophiles usually require formation of at least a catalytic amount of the anion.\(^{41}\) Thiolates are less basic but more nucleophilic than alkoxides.

The \(\beta\)-chloroacrylamide \(1a\) was initially treated with 1.1 equivalents of benzenethiol in toluene at reflux for 7 hours, leading to a complex mixture of products. The major product was the \(\beta\)-phenylthioacrylamide \(47a\), isolated as a white crystalline solid in 36% yield. Substitution of the chloride in \(1a\) by thiophenol under neutral conditions is significant, and is consistent with the increased nucleophilicity of the thiol compared to ethanol and methanol. On employment of basic conditions (1.1 equivalents of lithium thiolate, generated *in situ* from reaction of benzenethiol and \(n\)-buthyllithium), an improved yield of 66% was obtained for the \(\beta\)-phenylthioacrylamide \(47a\) (Scheme 24).

\[
\text{PhS} \quad \begin{array}{c}
\text{O} \\
\text{Cl} \\
\text{NH} \text{Tol}
\end{array} \quad \begin{array}{c}
\downarrow \\
\text{PhSH, toluene,} \\
\Delta, 7\text{ h, 36\%}
\end{array} \quad \begin{array}{c}
\text{PhS} \quad \begin{array}{c}
\text{O} \\
\text{PhS} \\
\text{NH} \text{Tol}
\end{array} \\
\end{array} \quad \begin{array}{c}
\text{LISPh, THF,} \\
\text{rt, 6 h, 66\%}
\end{array}
\]

*Scheme 24*

Meanwhile, treatment of the benzylthio \(\beta\)-chloroacrylamide \(1v\) under the basic conditions described above resulted in a mixture of the mono- and diaddition products \(47v\) and \(48v\). Following chromatographic purification, \(47v\) and \(48v\) were isolated in yields of 54% and 41% respectively (Scheme 25).

\[
\text{BnS} \quad \begin{array}{c}
\text{O} \\
\text{Cl} \\
\text{NH} \text{Bn}
\end{array} \quad \begin{array}{c}
\downarrow \\
\text{LISPh, THF,} \\
\text{rt, 5 h}
\end{array} \quad \begin{array}{c}
\text{BnS} \quad \begin{array}{c}
\text{O} \\
\text{PhS} \\
\text{NH} \text{Bn}
\end{array} \\
\end{array} \quad \begin{array}{c}
\text{BnS} \quad \begin{array}{c}
\text{O} \\
\text{PhS} \quad \text{SSPh}
\end{array} \\
\end{array}
\]

*Scheme 25*

Finally, treatment of the sulfoxide \(18a\) with 1.1 equivalents of benzenethiol in toluene at reflux for 7 hours, led to a 1.1:1 mixture of the \(Z\) and \(E\) isomers of the monoaddition product \(49a\), in addition to 12% of the sulfide \(47a\) (Scheme 26). Following chromatographic purification, the \(Z\) and \(E\) isomers of \(49a\) were isolated as an inseparable
mixture in 63% yield in the same Z:E ratio as a white solid, and 47a was isolated as a white solid in 12% yield.

![Scheme 26](image)

**Selenium Nucleophiles**

One equivalent of sodium phenyl selenide, prepared as described by Sharpless by treatment of diphenyl diselenide in ethanol with two equivalents of sodium borohydride, was added to an ethanolic solution of 1a. Following stirring at room temperature for 16 hours, the β-phenylselenoacrylamide 50a was isolated as a single isomer, presumably Z, in 60% yield (Scheme 27).

![Scheme 27](image)

**Conclusion**

The β-chloroacrylamides at the sulfide, sulfoxide and sulfone levels of oxidation act as very efficient Michael acceptors, and readily undergo substitution reactions with carbon, nitrogen, oxygen, sulfur and selenium based nucleophiles, demonstrating that the carbon framework can be easily extended and new functionality introduced at the β-position as summarised in Scheme 28 for the sulfides. In most instances, the nucleophile replaces the chloro substituent with retention of stereochemistry. With the oxygen nucleophiles, a second addition can occur leading to acetals, while with the nitrogen nucleophiles, E-Z isomerism occurs in the resulting enamine derivatives. The ratio of the E/Z isomers can be rationalised on the basis of the substituent and the level of oxidation.
Experimental

All solvents were distilled prior to use as follows: dichloromethane was distilled from phosphorous pentoxide and ethyl acetate was distilled from potassium carbonate, ethanol and methanol were distilled from magnesium in the presence of iodine. Acetone was distilled from potassium permanganate and toluene was distilled from sodium and stored over 4Å molecular sieves. Dimethylformamide was stored overnight over calcium hydride, then distilled and stored over 4 Å molecular sieves. Organic phases were dried using anhydrous magnesium sulphate.

\(^1\)H (300 MHz) and \(^{13}\)C (75.5 MHz) NMR spectra were recorded on a Bruker (300 MHz) NMR spectrometer. \(^1\)H (270 MHz) and \(^{13}\)C (67.8 MHz) NMR spectra were recorded on a Jeol GSX (270 MHz) NMR spectrometer. \(^1\)H (60 MHz) NMR spectra were recorded on a Jeol PMX-60SI spectrometer. All spectra were recorded at room temperature (~20°C) in deuterated chloroform (CDCl\(_3\)) unless otherwise stated using tetramethylsilane (TMS) as an internal standard. Chemical shifts were expressed in parts per million (ppm) and coupling constants in Hertz (Hz).

Elemental analyses were performed by the Microanalysis Laboratory, National University of Ireland, Cork, using a Perkin-Elmer 240 elemental analyzer. Melting points were carried out on a uni-melt Thomas Hoover Capillary melting point apparatus. Mass spectra were recorded on a Kratos Profile HV-4 double focusing high resolution mass
spectrometer (EI), a Waters/Micromass LCT Premier Time of Flight spectrometer (ESI) and a Waters/Micromass Quattro Micro triple quadrupole spectrometer (ESI). Infrared spectra were recorded as potassium bromide (KBr) discs for solids or thin films on sodium chloride plates for oils on a Perkin-Elmer Paragon 1000 FT-IR spectrometer. Thin layer chromatography (TLC) was carried out on precoated silica gel plates (Merck 60 PF254). Column chromatography was performed using Merck silica gel 60. Visualisation was achieved by UV (254nm) light detection, iodine staining, vanillin staining and ceric sulfate staining.

The syntheses of β-chloroacrylamides 1a-1u, sulfoxides 18a-18m and sulfone adducts 23a-23m have been described elsewhere. Selected experimental data, including representatives of each of the synthetic methods, are given below-full experimental procedures and spectral data for all the compounds described in the paper are given in the ESI.

**Addition of Carbon Nucleophiles**

**Addition of the enolate of diethyl malonate**

\[ N-(4-Methylphenyl)-4,4-di(ethoxycarbonyl)-2-(phenylthio)-2-pentenamide \]

\( 2a \)

Diisopropylamine (0.5 mL, 3.6 mmol) was added to a flask containing THF (20 mL). The stirred solution was cooled to 0 °C and n-butyllithium (1.5 mL, 1.6 M in hexane, 3.78 mmol) was added dropwise via syringe. After 20 min, diethyl malonate (0.6 mL, 3.6 mmol) was added and the reaction mixture was stirred for a further 20 min. A solution of 1a (1.00 g, 3.3 mmol) in THF (20 mL) was then added dropwise. A bright yellow colour appeared instantly. After 1 h the reaction was complete (by TLC analysis) and was quenched with saturated aqueous ammonium chloride (20 mL). CH₂Cl₂ (20 mL) was added and the phases were separated. The aqueous phase was extracted with CH₂Cl₂ (2 × 10 mL) and the combined organic layers were washed with aqueous sodium bicarbonate (2 × 10 mL), brine (2 × 10 mL), dried and evaporated to give \( 2a \) as a yellow, low-melting solid. Purification by chromatography using ethyl acetate-hexane (20:80) as eluent gave \( 2a \) (1.23 g, 80%) as a yellow, crystalline solid. The product contained a minor isomer which could not be separated by chromatography. The ratio was estimated to be (27:1) by
$^1$H NMR spectroscopic integration; mp 68–70 °C; (Found C, 64.56; H, 5.77; N, 2.95; S, 7.13. $C_{23}H_{25}NO_5S$ requires C, 64.62; H, 5.89; N, 3.28; S, 7.50%); $\nu_{\text{max}}$/cm$^{-1}$ (KBr) 3354 (br NH), 1749, 1736 (CO ester), 1664 (CO $\alpha$,$\beta$-unsaturated amide); $\delta_H$ (270 MHz, CDCl$_3$) 1.29 (6H, t, $J$ 7.1, 2 $\times$ CH$_2$CH$_2$O), 2.31 (3H, s, ArCH$_3$), 4.22 (4H, q, $J$ 7.1, 2 $\times$ CH$_2$O), 4.94 [1H, d, $J$ 10, C(4)H], 7.06-7.57 (9H, m, ArH), 7.75 (1H, d, $J$ 10, CH(3)=$\alpha$), 8.62 (1H, br s, NH); $\delta_C$ (67.8 MHz, CDCl$_3$) 13.9 (CH$_3$CH$_2$O), 20.8 (ArCH$_3$), 54.4 [C(4)H], 62.1, 120.1, 127.2, 127.8, 129.0, 129.2 (aromatic CH), 132.3, 133.1, 134.5, 134.7 (quaternary aromatic C and SC=), 141.2 (CH=), 160.9 (CO amide), 166.3 (CO ester); MS $m/z$ 427 (M$^+$, 25%), 381 (25%), 267 [30%, M$^+$-CH$_2$(CO$_2$Et)$_2$], 109 (91%). Signals for the minor isomer were seen in $^1$H and $^{13}$C NMR spectra at 5.42 [1H, d, $J$ 10, C(4)H], 6.82 (1H, d, $J$ 10, CH=); all other signals were identical to the major isomer.

**Alkylation of 2c**

*N-Phenylmethyl-4,4-di(ethoxycarbonyl)-2-phenylthiohept-2,6-dienamide 3a*

Potassium carbonate (0.19 g, 1.41 mmol) was added to a solution of 2c (0.30 g, 0.70 mmol) in acetonitrile (6 mL). A solution of allyl bromide (0.12 mL, 1.41 mmol) in acetone (3 mL) was added and the reaction mixture was stirred overnight under nitrogen. Ether (10 mL) was added to precipitate the salts, and the mixture was filtered through a celite plug. The filtrate was then dried and the solvent evaporated to give the crude product as a brown oil. Following chromatography on silica gel using 15:85 ethyl acetate-hexane, 3a was isolated as a white solid (0.09 g, 27%); mp 66–68 °C; (Found C, 66.99; H, 6.15; N, 3.07; S, 7.10; $C_{26}H_{29}NO_5S$ requires C, 66.79; H, 6.25; N, 2.90; S, 6.86%); $\nu_{\text{max}}$/cm$^{-1}$ (KBr) 3374 (NH), 1749, 1736 (CO saturated ester), 1666 (CO amide); $\delta_H$ (300 MHz, CDCl$_3$) 1.19 (6H, t, $J$ 7.1, 2 $\times$ OCH$_2$CH$_3$), 2.93 [2H, d, $J$ 7.4, C(5)H$_2$], 3.96-4.21 (4H, 2 $\times$ sym m, 2 $\times$ OCH$_2$CH$_3$), 4.36 (2H, d, $J$ 5.8, NCH$_2$Ph), 5.07-5.17 [2H, m, C(7)H$_2$=$\alpha$], 5.71-5.88 [1H, m, C(6)H$\beta$=$\beta$], 6.73-6.80 (2H, m, ArH), 6.94-7.27 (9H, m, ArH, br s at 7.00 for NH), 7.97 [1H, s, C(3)H$\alpha$=$\alpha$]; $\delta_C$ (75.5 MHz, CDCl$_3$) 14.3 (CH$_3$, OCH$_2$CH$_3$), 41.7 [CH$_2$, C(5)H$_2$], 44.5 (CH$_2$, NCH$_2$Ph), 60.7 [C, C(4)], 62.4 (CH$_2$, OCH$_2$CH$_3$), 120.1 [CH$_2$, C(7)H$_2$=$\alpha$], 127.0, 127.6, 127.8, 128.9, 129.0 [CH, aromatic CH, C(6)H$\beta$=$\beta$], 129.6 (C, =CPh), 129.7, 132.5 [CH, aromatic CH, C(6)H$\alpha$=$\alpha$], 134.3, 138.0 (C, aromatic C), 146.2 [CH, C(3)H$\beta$=$\beta$], 164.1 (C, amide CO), 169.3 (C, ester CO); MS $m/z$ 467 (6%, M$^+$), 394 [3%, (M-CO$_2$Et)$^+$], 84 (100%).
Addition of the enolate of ethyl acetoacetate

**N-(4-Methylphenyl)-4-ethoxycarbonyl-2-(phenylthio)-5-oxo-2-hexenamide 4a**

Ethyl acetoacetate (0.17 g, 1.32 mmol) was added to a freshly prepared solution of sodium ethoxide [using sodium (30 mg, 1.32 mmol) and ethanol (10 mL) at 0 °C] and stirred for 30 min. A solution of β-chloroacrylamide 1a (0.2 g, 0.66 mmol) in ethanol (3 mL) was added. After stirring for 3 h (while slowly returning to room temperature), the reaction mixture was quenched with water (10 mL). CH₂Cl₂ (20 mL) was added and the phases were separated. The organic layer was washed with brine (2 × 10 mL), dried and evaporated. Excess ethyl acetoacetate was removed under vacuum at 1 mmHg. Purification by recrystallisation from ether-CH₂Cl₂-hexane (10:5:75) gave what is tentatively assigned as 4a (29 mg, 11%) as white crystals in enol tautomeric form; mp 184−185 °C; νmax/cm⁻¹ (KBr) 3480 (br NH), 1711 (CO conjugated ester), 1654, 1592 (CO α,β-unsaturated amide); δH (270 MHz, CDCl₃) 1.22 (3H, t, J 7, CH₃CH₂O), 2.34 (3H, s, ArCH₃), 2.42 [3H, s, C(6)H₃], 4.19 (2H, q, J 7, OCH₂), 7.01-7.57 (11H, m, ArH and C(5)H= and NH); δC (67.8 MHz, CDCl₃) 14.1 (CH₃, CH₃CH₂O), 19.4 [CH₃, C(6)H₃], 21.2 (CH₃, ArCH₃), 60.9 (CH₂, CH₂O), 109.6 [C, C(4)], 127.5, 128.6, 129.5, 130.6, 134.0 (CH, ArCH), 128.2, 131.8, 139.2 (3 × C, aromatic C and PhSC=), 135.8 [CH, C(3)H], 150.6 (C, =COH), 160.8, 165.4 (2 × C, CO amide, CO ester).

Addition of n-Bu₂CuLi

**N-(4-Methylphenyl)-2-(phenylthio)-Z-2-heptenamide 7a**

Ether (25 mL) was added to a flask containing CuI (250 mg, 1.32 mmol) which had been freshly purified. The suspension was cooled to −30 °C, n-butyllithium (1.65 mL, 1.6 M in hexane, 2.64 mmol) was added and stirring was continued for 30 min, after which time the solution was brown and opaque. The reaction mixture was cooled to −78 °C and β-chloroacrylamide 1a (0.20 g, 0.66 mmol) in ether (10 mL) was added quickly. The reaction was complete after 30 min at a reaction temperature of −50 °C. Saturated aqueous ammonium chloride (10 mL) was added and stirred for 15 min while the reaction mixture was warmed to room temperature. Saturated aqueous ammonium chloride (10
mL) and ether (10 mL) were added and the solution was filtered through a layer of celite. Separation of the phases followed by washing of the organic phase with brine (2 × 20 mL), drying and evaporation gave a yellow oil. Purification by chromatography using ethyl acetate-hexane (5:95) as eluent gave 7a-Z (85 mg, 40%) as a light yellow solid; mp 43–45 °C; (Found C, 73.40; H, 7.00; N, 4.21; S, 9.84. C_{20}H_{23}NOS requires C, 73.81; H, 7.21; N, 4.30; S, 9.85%); ν_max/cm⁻¹ (film) 3354 (br NH), 1674, 1594 (CO α,β-unsaturated amide); δ_H (270 MHz, CDCl₃) 0.92 [3H, t, J 7, C(7)H₃], 1.29-1.37 [2H, m, C(6)H₂], 1.40-1.54 [2H, m, C(5)H₂], 2.28 (3H, s, ArCH₃), 2.49-2.58 [2H, dt, J 7, 7, C(4)H₂], 7.06-7.38 (9H, m, ArH), 7.75 [1H, t, J 7, C(3)H=], 8.79 (1H, br s, NH); δ_C (67.8 MHz, CDCl₃) 13.4 [CH₃, C(7)H₃], 20.3 (CH₃, ArCH₃), 22.0 [CH₂, C(6)H₂], 28.9 [CH₂, C(5)H₂], 30.0 [CH₂, C(4)H₂], 119.6, 125.9, 126.7, 128.9 (CH, aromatic CH), 125.7, 133.6, 134.2, 134.7 (4 × C, aromatic C and SC=), 153.5 [CH, C(3)H=], 161.8 (C, CO); MS m/z 325 (M⁺, 17%), 149 (15%), 107 [22%, (NHTol)⁺], 96 (100%). A compound which was detected in a mixture of side-products was tentatively assigned as 21-E (total wt = 5 mg, 2 %). δ_H (270 MHz, CDCl₃) 0.93 [3H, t, J 7, C(7)H₃], 1.36-1.57 [4H, m, C(6)H₂, C(5)H₂], 2.27 (3H, s, ArCH₃), 2.76-2.79 [2H, dt, J 7, 7, C(4)H₂], 6.74 [1H, t, J 7, C(3)H=], 7.05-7.29 (9H, m, ArH), 8.49 (1H, br s, NH).

**Addition of Me₂CuLi**

**N-Benzy l-2-phenylthio-2-butenamide 10c**

Cul (0.42 g, 2.18 mmol) was suspended in dry ether (20 mL) and the flask was cooled to –78 °C under nitrogen. Methyl lithium (2.7 mL, 1.6 M solution in ether, 4.36 mmol) was added and the mixture was stirred for 10 min, during which time it changed from yellow to colourless. In a separate flask, 1c (0.33 g, 1.09 mmol) was dissolved in ether (20 mL) and also cooled to –78 °C. The organocuprate solution was then allowed to settle and added to the solution of 1c using a cannula. The reaction vessel was maintained at –78 °C for 2.25 hours, and on removal from the cold bath the reaction was rapidly quenched with saturated aqueous ammonium chloride (5 mL). After stirring for 10 min, the solution was filtered through a celite plug, the layers were separated and the aqueous layer was washed with ether (2 × 20 mL). The combined organic layers were washed with brine (20 mL), dried, and the solvent evaporated at reduced pressure to give the crude product, which was shown by ¹H NMR spectroscopic
analysis to contain a 1:16 ratio of starting material to the Z isomer of the adduct 10c. After chromatography, the pure product 10c was isolated as an off-white solid (0.11 g, 75%); \( \nu_{\text{max}}/\text{cm}^{-1} \) (film) 3355 (NH), 1653 (CO), 1608, 1581 (C=C), 1511; \( \delta_H \) (300 MHz, CDCl\(_3\)) 2.09 [3H, d, \( J = 7.0 \), C(4)H\(_3\)], 4.43 (2H, d, \( J = 5.9 \), NCH\(_2\)Ph), 6.89-6.99 (2H, m, ArH), 7.10-7.39 (9H, m, NH, ArH), 7.75 (1H, q, \( J = 7.0 \), C(3)H\(_3\)); \( \delta_C \) (75.5 MHz, CDCl\(_3\)) 16.7 [CH\(_3\), C(4)H\(_3\)], 43.9 (CH\(_2\), NCH\(_2\)Ph), 126.1, 126.9 (CH, aromatic CH), 127.0 (C, aromatic C), 127.2 127.7, 128.5, 129.3 (CH, aromatic CH), 134.8, 137.9 (C, aromatic C =CS), 148.1 [CH, C(3)H=], 164.3 (C, CO); MS \( m/z \) 283 (M\(^+\), 48%), 268 [5%, (M-CH\(_3\))\(^+\)], 174 [8%, (M-PhS)\(^+\)], 149 [21%, (PhS=C(CH\(_3\))\(^+\)], 134 [24%, (CONHCH\(_2\)Ph\(^+\)], 106 [45%, (NHCH\(_2\)Ph\(^+\)], 91 [100%, (CH\(_2\)Ph\(^+\)], 77 [23%, (C\(_6\)H\(_5\))\(^+\)].

**Addition of Ph\(_2\)CuLi**

**N-Benzyl-3-phenylpropynamide 11c**

To a solution of CuI (0.38 g, 1.98 mmol) in ether (30 mL) at –78 °C was added phenyl lithium (2.2 mL, 1.8 M solution in ether, 3.96 mmol) by syringe. This was stirred for 10 min under nitrogen. In a separate flask 1c (0.30 g, 0.99 mmol) was dissolved in ether (20 mL) and cooled to –78 °C. The cuprate solution was added to the reaction vessel using a cannula, and the reaction mixture stirred for 2 h at –78 °C, at which point it was allowed to warm to room temperature. The reaction was quenched with aqueous ammonium chloride (5 mL) and filtered to remove the copper salts. The layers were separated and the aqueous layer washed with ether (10 mL). The combined organic layers were dried, and the solvent evaporated at reduced pressure to give the crude product mixture as an oil. After chromatography on silica gel using 20:80 ethyl acetate/hexane as eluent, the propynamide 11c was isolated as an oil (0.19 g, 83%); \( \nu_{\text{max}}/\text{cm}^{-1} \) (film) 3279 (NH), 3061, 3032 (CH), 2222 (C=C), 1636 (CO); \( \delta_H \) (270 MHz, CDCl\(_3\)) 4.49 (2H, d, \( J = 5.9 \), NCH\(_2\)Ph), 6.55 (1H, br s, NH), 7.05-7.60 (10H, m, ArH); \( \delta_C \) (67.8 MHz, CDCl\(_3\)) 43.9 (NCH\(_2\)Ph), 83.0, 85.0 (C=C), 120.2 (aromatic C), 127.2, 127.9, 128.7, 129.0, 129.7, 132.1 (aromatic CH), 137.4 (aromatic C), 153.3 (CO).

**Addition of iPr\(_2\)CuMgCl**

**N-Benzyl-4-methyl-2-(phenylthio)-2-pentenamide 13c**
CuI (0.26 g, 1.35 mmol) was dissolved in ether (20 mL) and cooled to –78 °C. i-Propyl magnesium chloride (1.4 mL, 2.0 M solution in ether, 2.71 mmol) was added by syringe and the solution was stirred for 15 min. The starting material 1c (0.21 g, 0.68 mmol) was dissolved in ether (10 mL) at room temperature and this solution was added to the reaction vessel by syringe, and this mixture was stirred for 2.5 h. The reaction was then quenched with water (10 mL) and the solution was filtered through a Celite® plug. The layers were separated, and the aqueous layer was washed with ether (2 × 10 mL). The combined organic layers were dried, and the solvent was evaporated to give a crude mixture containing a 1.13:1.0 ratio of starting material to product 13c-Z, which also contained a trace of 13c-E; mp 83–85 °C; νmax/cm⁻¹ (film) 3334 (NH), 1652 (CO), 1607, 1583 (C=C), 1513; δH (300 MHz, CDCl₃) 1.08 [6H, d, J 6.7, CH(C₃H₅)₂], 3.00–3.18 [1H, m, C₃H₅(CH₃)₂], 4.02 (2H, d, J 5.9, NCH₂Ph), 6.87–6.96 (2H, m, ArH), 7.10-7.38 (9H, m, ArH, NH), 7.48 [1H, d, J 9.9, C(3)H=]; δC (75.5 MHz, CDCl₃) 21.9 [CH₃, CH(CH₃)₂], 30.4 [CH, CH(CH₃)₂], 43.9 (CH₂, NCH₂Ph), 123.4 (C, aromatic C), 126.1, 126.8, 127.2, 127.2, 128.5, 129.4 (CH, aromatic CH), 135.2, 137.9 (C, aromatic C, =CS), 159.1 [CH, C(3)H=], 164.4 (C, CO); MS m/z 311 (M⁺, 73%), 268 [17%, (M-C₃H₇)⁺], 177 [13%, (CH=CSPhCONH)⁺], 162 [16%, (CH=CSPhCO)⁺], 110 (42%, PhSH), 106 [35%, (NHCH₂Ph)⁺], 91 [100%, (CH₂Ph)⁺], 77 [34%, (C₆H₅)⁺]. The E isomer 13c-E was tentatively identified by a signal at δH 6.45 [d, J 10.0, =C(3)H].

**Nitrogen Nucleophiles**

**Addition of primary and secondary amines**

**N-(4-Methylphenyl)-3-N′,N′-dimethylamino-2-(phenylthio)propenamide 14a**

β-Chloroacrylamide 1a (200 mg, 0.66 mmol) was added to dimethylamine (5.6 M in ethanol, 3 mL, 17 mmol) with stirring. After stirring for 15 min the reaction was complete (by TLC analysis) and CH₂Cl₂ (10 mL) and water (10 mL) were added. The phases were separated and the aqueous layer was washed with CH₂Cl₂ (2 × 5 mL). The combined organic layers were washed with aqueous saturated aqueous ammonium chloride (2 × 10 mL), brine (2 × 10 mL), dried and evaporated to give β-aminopropenamide 14a (177 mg, 85%) as a white, crystalline solid. Purification by recrystallisation from ethanol gave 14a (0.16 g, 75 %) as a white, crystalline solid; mp
124–125 °C; (Found C, 69.02; H, 6.40; N, 9.28; S, 10.20. C₁₈H₂₀N₂OS requires C, 69.20; H, 6.45; N, 8.97; S, 10.26%); ν<sub>max</sub>/cm<sup>-1</sup> (KBr) 3338 (br NH), 1652, 1583 (CO<sub>α,β</sub>-unsaturated amide); δ<sub>H</sub> (270 MHz, CDCl<sub>3</sub>) 2.26 (3H, s, ArCH₃), 3.18 [6H, s, N(CH₃)₂], 7.04-7.39 (9H, m, ArH), 8.29 [1H, s, C(3)H=], 8.86 (1H, br s, NH); δ<sub>C</sub> (67.8 MHz, CDCl<sub>3</sub>) 20.7 (CH₃, ArCH₃), 42.7 [CH₃, br, N(C₃H₃)₂], 83.0 (SC=), 119.7, 124.8, 125.2, 128.7, 129.2 (aromatic CH), 132.5, 136.5, 139.5 (quaternary aromatic C), 154.1 [C(3)H=], 167.1 (CO); MS m/z 312 (M⁺, 15%), 285 (13%), 271 (15%), 178 (12%).

**Addition of hydroxylamine**

**N-(4-Methylphenyl)-3-oxime-2-(phenythio)propanamide 29a**

A solution of 1a (0.15 g, 0.50 mmol) in ethanol (5 mL) and water (1 mL) was stirred at room temperature. Potassium carbonate (83 mg, 0.78 mmol) and hydroxylamine hydrochloride (72 mg, 1.04 mmol) were added and the reaction mixture was warmed at 60 °C for 1 min. After stirring for 5 h at room temperature, the reaction was complete by TLC analysis, and CH₂Cl₂ (10 mL) and saturated aqueous ammonium chloride (10 mL) were added. The phases were partitioned and the aqueous layer was washed with CH₂Cl₂ (2 × 10 mL). The combined organic layers were washed with brine (2 × 10 mL), dried and evaporated. Purification by trituration with hexane gave 29a-Z and 29a-E (0.11 g, 74%) Note: The E and Z isomers interconvert on silica gel (2 D analysis), and slowly on standing at room temperature. Thus a pure sample of either isomer could not be obtained; mp 124–126 °C; (Found C, 63.64; H, 5.70; N, 9.16; S, 10.44. C₁₆H₁₆N₂O₂S requires C, 63.98; H, 5.37; N, 9.33; S, 10.67%); ν<sub>max</sub>/cm<sup>-1</sup> (KBr) 3281 (br NH), 1654, 1597 (CO<sub>α,β</sub>-unsaturated amide); δ<sub>H</sub> (270 MHz, acetone-d<sub>6</sub>) tentatively assigned Z; 2.27 (3H, s, ArCH₃), 4.69 (1H, d, J 8, CHS), 7.11-7.54 (9H, m, ArH), 7.59 (1H, d, J 8 CH=N), 9.50 (1H, br s NHTol), 10.11-10.27 (1H, br s, OH); tentatively assigned E; 2.27 (3H, s, ArCH₃), 3.09 (1H, br s, OH), 5.39 (1H, d, J 8, CHS), 7.00 (1H, d, J 8, CH=N), 7.11-7.54 (9H, m, ArH), 9.50 (1H, br s, NHTol); δ<sub>C</sub> (67.8 MHz, acetone-d<sub>6</sub>) 20.8 (ArCH₃), 46.0, 53.1° (CHS), 120.5, 128.9, 130.0, 130.4, 133.5 (aromatic CH), 134.2, 134.3°, 137.0°, 137.1 (quaternary aromatic C), 146.5, 147.3° (CH=N), 166.2, 166.4° (CO); MS m/z 300 (M⁺, 1%), 284 (10%, M⁺-O), 268 (2%, M⁺-NHOH), 110 (78%), 107 (100%).
Major isomer.

Ratio: in acetone-\(d_6\) 1:1.37 (Z:E)

in deuterated methanol 1:1.03 (Z:E)

in deuterated DMSO-\(d_6\) 1:1.43 (Z:E)

**Addition of ammonia**

*N-(4-Methylphenyl)-3-amino-2-(phenythio)propanamide 30a and 31a*

Aqueous ammonia (35%, 73 μl, 1.45 mmol) was added to a solution of 1a (200 mg, 0.66 mmol) in acetone (4 mL). After 74 h the reaction was incomplete by TLC analysis, and a further aliquot of aqueous ammonia (73 μl, 1.45 mmol) was added. Following 24 h of stirring at room temperature, only trace amounts of 1a remained. CH\(_2\)Cl\(_2\) (10 mL) and saturated aqueous ammonium chloride (10 mL) were added and the phases separated, the aqueous layer was washed with CH\(_2\)Cl\(_2\) (2 × 10 mL). The combined organic layers were washed with brine (2 × 10 mL), dried and evaporated. Purification by chromatography using ethyl acetate-hexane (20:80) as eluent gave a mixture of tautomers and geometrical isomers (140 mg, 75%), which could not be isolated; mp 83–85 °C; (Found C, 67.05; H, 5.90; N, 9.92; S, 11.52. C\(_{16}\)H\(_{16}\)N\(_2\)OS requires C, 67.58; H, 5.67; N, 9.85; S, 11.28%);

\(\nu_{max}/\text{cm}^{-1}\) (KBr) 3363 (br NH), 1651, 1590 (CO \(\alpha,\beta\)-unsaturated amide); The following signals were distinguishable in the \(^1\)H NMR spectrum: \(\delta_H\) (270 MHz, CDCl\(_3\)) 1.37 (d, \(J\) 12), 2.01, 2.07 (2 × s), 2.27 (3 H, s, ArCH\(_3\)), 2.59, 2.67 (2 × s), 5.20-5.50 (br s), 7.05-7.39 (9 H, m, ArH), 8.35 (t, \(J\) 7), 8.35, 8.40 (s), 8.48 (br s, NH); \(\delta_C\) (67.8 MHz, CDCl\(_3\)) major peaks at 20.8, 119.9, 125.4, 129.2, 150.6; MS \(m/z\) 284 (M\(^+\), 15%), 224 (18%), 149 (25%), 134 [22%, (PhS=C=CH\(^+\))\(^+\)], 107 (100%).

**Oxygen Nucleophiles**

*Formation of \(\beta,\beta\)-dimethoxyamid*e

*N-(4-Methylphenyl)-3,3-dimethoxy-2-(phenylthio)propanamide 34a*
From a solution of sodium (50 mg, 2.17 mmol) in methanol (10 mL), a 6.4 mL portion was added to a solution of 1a (0.20 g, 0.66 mmol) in methanol (4 mL). After stirring for 1h the reaction was complete by TLC analysis. Saturated aqueous ammonium chloride (10 mL) and ether (15 mL) were added and the phases were separated. The aqueous layer was extracted with ether (2 × 5 mL) and the combined organic layers were washed with brine (2 × 10 mL), dried and evaporated to give 34a (199 mg, 91%) as a white, crystalline solid which did not require further purification; mp 103−105 °C; (Found C, 64.83; H, 6.69; N, 4.40; S, 10.20. C_{18}H_{21}NO_{3}S requires C, 65.23; H, 6.39; N, 4.23; S, 9.67%); ν_{max}/cm^{-1} (KBr) 3282 (br NH), 1657, 1599 (CO amide); δ_{H} (270 MHz, CDCl_{3}) 2.30 (3H, s, ArCH_{3}), 3.48 (3H, s, OCH_{3}), 3.53 (3H, s, OCH_{3}), 3.98 (1H, d, J 4, C(3)H), 7.09-7.47 (9H, m, ArH), 8.54 (1H, br s, NH); δ_{C} (67.8 MHz, CDCl_{3}) 20.9 (ArCH_{3}), 56.3, 56.9 (OCH_{3}), 58.0 (CHS), 105.3 [C(3)H], 120.5, 127.6, 128.9, 129.3, 129.9 (aromatic CH), 133.8, 134.2, 135.1 (aromatic C), 166.6 (CO); MS m/z 331 (M^{+}, 25%), 271 (33%), 75 [100%, [CH(OMe)]+].

Reaction with lithium methoxide

N-(4-Methylphenyl)-Z-3-methoxy-2-(phenylthio)propenamide 33a

A 1 mL aliquot of a solution of methanol (87 µl, 2.16 mmol) in THF (5 mL) was added to a flask containing THF (2 mL), and the solution was cooled to 0 °C. n-Butyllithium (0.29 mL, 1.6 M in hexane, 0.46 mmol) was added and the reaction mixture was stirred for 10 min before cooling to −78 °C. A solution of 1a (100 mg, 0.33 mmol) in THF (2 mL) was also cooled to −78 °C and the methoxide solution was added slowly by syringe. The reaction mixture was allowed to warm up slowly in the cooling bath. After stirring for 3.5 h at a temperature of −5 °C, the reaction was complete by TLC analysis and was quenched with aqueous saturated aqueous ammonium chloride (10 mL). The aqueous phase was extracted with ether (2 × 10 mL), the combined organic layers were washed with brine (2 × 10 mL), dried and evaporated to give crude mixture containing 34a and 33a (1:6). Purification by chromatography using ethyl acetate-hexane (25:75) as eluent gave 33a (59 mg, 60%) (with < 10% dimethoxypropanamide 34a) as a white, crystalline solid; ν_{max}/cm^{-1} (KBr) 3349 (br NH), 1657, 1598 (CO amide); δ_{H} (270 MHz, CDCl_{3})
2.28 (3H, s, ArCH₃), 4.00 (3H, s, OCH₃), 7.07-7.47 (9H, m, ArH), 8.17 [1H, s, C(3)H=], 8.70 (1H, br s, NH); δC (67.8 MHz, CDCl₃) 20.8 (ArCH₃), 62.6 (OCH₃), 101.5 (SC=), 120.0, 126.0, 126.4, 128.7, 128.9 (aromatic CH), 133.8, 135.0, 135.3 (aromatic C), 163.3 (CO), 166.1 [C(3)H=]; MS m/z 299 (M⁺, 100%), 193 (50%, M⁺-NHTol), 165 (50%, M⁺-CONHTol).

Addition of ethylene glycol
2-[N-(4-Methylphenyl)-2-(phenylthio)acetamide]-1,3-dioxolane 39a

n-Butyllithium (0.33 mL, 1.6 M in hexane, 0.52 mmol) was added to a solution of ethylene glycol (34 µl, 0.55 mmol) in THF (2 mL) at 0 °C. The solution was removed from the ice bath and allowed to warm to room temperature over 10 min. A solution of 1a (80 mg, 0.26 mmol) in THF (2 mL) was added rapidly to the reaction mixture. After stirring for 16 h the reaction was complete by TLC analysis, and saturated aqueous ammonium chloride (10 mL) and CH₂Cl₂ (10 mL) were added. The phases were separated, the aqueous layer was extracted with CH₂Cl₂ (2 × 10 mL) and the combined organic layers were washed with brine (2 × 10 mL), dried and evaporated to give the crude acetal. Purification by chromatography using ethyl acetate-hexane (30:70) as eluent gave 39a (51 mg, 60%) as a white, crystalline solid; mp 102−104 °C; (Found C, 65.60; H, 5.54; N, 4.49; S, 9.40, C₁₈H₁₉NO₃S requires C, 65.63; H, 5.81; N, 4.25; S, 9.73%); νmax/cm⁻¹ (KBr) 3305 (br NH), 1657, 1605 (CO amide); δH (270 MHz, CDCl₃) 2.30 (3H, s, ArCH₃), 3.91-4.03 (2H, m, CH₂O), 4.07-4.20 (3H, contains d, J 2, CHS at δH 4.13) 5.49 [1H, d, J 2, C(3)H], 7.10-7.47 (9H, m, ArH), 8.58 (1H, br s, NH); δC (67.8 MHz, CDCl₃) 20.8 (ArCH₃), 58.7 (CHS), 65.8, 66.1 (2 × CH₂O), 102.8 (CHO), 119.9, 127.6, 129.3, 129.4, 131.0 (aromatic CH), 133.4, 134.2, 134.9 (aromatic C), 165.9 (CO); MS m/z 329 (M⁺, 2%), 257 [1%, M⁺-CO₂(CH₂)₂].

Addition of chiral diols
(4R,5R)-4,5-Dimethyl-2-[N-(4-methylphenyl)-2-(phenylthio)acetamide]-1,3-dioxolane 42a

n-Butyllithium (0.83 mL, 1.6 M in hexane, 1.32 mmol) was added to a solution of (2R, 3R)-2,3-butanediol 41a (125 mg, 1.39mmol) in THF (3 mL) at 0 °C. The reaction
mixture was removed from the ice bath and stirred at room temperature for 10 min. A solution of 1a (0.20 g, 0.66 mmol) in THF (3 mL) was added and a strong yellow colour developed. The reaction was complete by TLC analysis after stirring for 2 h at room temperature, and saturated aqueous ammonium chloride (10 mL) and ether (20 mL) were added. The phases were separated, the aqueous layer was extracted with CH₂Cl₂ (2 × 10 mL) and the combined organic layers were washed with brine (2 × 10 mL), dried and evaporated. Purification by chromatography using ethyl acetate-hexane (10:90 to 25:75) as eluent gave the two diastereomers (56:44) of 42a (0.15 g, 65%) as a white, crystalline solid; mp 86–88 °C; [α]D 20 –16.53 (c 7 in ethanol); (Found C, 67.52; H, 6.70; N, 4.40%); C₂₀H₂₃NO₃S requires C, 67.20; H, 6.49; N, 3.92%; νmax/cm⁻¹ (KBr) 3307 (br NH), 1660, 1605 (CO amide); δH (270 MHz, CDCl₃) 1.24-1.36 [6H, m, CH₂C(4) and CH₂C(5)], 2.30 (3H, s, ArCH₃), 3.70-3.91 [2H, m, C(4)H and C(5)H], 4.05, 4.07 (1H, d, J 2, CHS), 5.58, 5.63 [1H, d, J 2, C(2)H], 7.09-7.48 (9H, m, ArH), 8.55 (1H, br s, NH); δC (67.8 MHz, CDCl₃) 16.2, 16.4, 16.88, 16.91 [CH₂C(4) and CH₂C(5)], 20.8 (ArCH₃), 58.5, 59.3 (CHS), 79.4, 79.7, 80.3, 80.5 [C(4)H and C(5)H], 101.7, 101.9 [C(2)H], 119.6, 119.9, 127.4, 127.5, 129.0, 129.4, 130.7, 131.0 (aromatic CH), 133.6, 133.8, 135.0, 135.1 (aromatic C), 166.0, 166.1 (CO); MS m/z 357 (M⁺, 2%), 267 (4%), 115 {100%, [CCH₃(OCHCH₃)]⁺}.

**Intramolecular nucleophilic addition**

5,6-Dihydro-1,4-oxathiine-2-carboxanilide 46a

n-Butyllithium (1.19 mL, 1.99 mmol) was added to a solution of HMDS (0.53 mL, 1.99 mmol), in THF (8 mL) at 0 °C and the reaction mixture was stirred for 20 min. This solution was added dropwise to a stirred solution of N-phenyl-Z-3-chloro-2-[2-(hydroxyethyl)thio]propanamide 46a (0.45 g, 1.73 mmol) in THF (5 mL) also at 0 °C. The flask was removed from the ice bath and the reaction temperature was allowed to increase to room temperature. Stirring was continued for 48 h followed by quenching with saturated aqueous ammonium chloride (10 mL). CH₂Cl₂ (20 mL) was added, the layers were separated and the aqueous layer was extracted with CH₂Cl₂ (2 × 10 mL). The combined organic phase was washed with brine (3 × 20 mL), dried and evaporated to
dryness to give a viscous oil (367 mg, quantitative). Purification by chromatography using ethyl acetate-CH₂Cl₂-hexane (25:5:70) as eluent gave 46a (156 mg, 41%) as a yellow crystalline solid; mp 131–133 °C; (Found C, 59.60; H, 5.07; N, 5.96; S, 14.72. C₁₁H₁₁NO₂S requires C, 59.71; H, 5.01; N, 6.33; S, 14.49%); v_max/cm⁻¹ (KBr) 3216 (br NH), 1632, 1602 (CO α,β-unsaturated amide); δ_H (270 MHz, CDCl₃) 3.01 (2H, dd, J 5, 5, C_H₂S), 4.42 (2H, dd, J 5, 5, C_H₂O), 7.07-7.64 (5H, m, Ar_H), 7.64 (1H, br s, N_H), 7.75 [1H, s, C(3)H=]; δ_C (67.8 MHz, CDCl₃) 24.1 (C_H₂S), 66.3 (C_H₂O), 101.8 (SC=), 119.9, 124.2, 129.0 (aromatic CH), 137.8 (aromatic C), 148.5 (OCH=), 162.6 (CO); MS m/z 221 (M⁺, 50%), 129 (100%, M⁺-PhNH), 93 [82%, (PhNH₂)+], 101 (18%, M⁺-CONHPh), 77 (32%).

**Sulfur Nucleophiles**

**N-(4-Methylphenyl)-2,3-di(phenylthio)propenamide 47a**

A) Using thiophenolate anion

n-Butyllithium (0.45 mL, 1.6 M in hexane, 0.73 mmol) was added to a stirred solution of thiophenol (81 µl, 0.79 mmol) in THF (2 mL) at 0 °C. After stirring for 10 min at 0 °C and for 20 min at room temperature, a solution of 1a (0.20 g, 0.66 mmol) in THF (3 mL) was added. After 2 h a further equivalent of lithium thiophenolate [from n-butyllithium (0.41 mL, 1.6 M in hexane, 0.66 mmol) and thiophenol (75 µl, 0.73 mmol)] was added. The reaction was complete by TLC analysis after 6 h and saturated aqueous ammonium chloride (10 mL) and ether (20 mL) were added. The phases were separated, the aqueous phase was extracted with ether (2 × 10 mL) and the combined organic layers were washed with brine (3 × 10 mL), dried and evaporated. Trituration with hexane gave 47a (165 mg, 66%) as a white, crystalline solid; mp 108–110 °C; spectroscopic characteristics are identical to those described previously.¹⁵

B) Using thiophenol

Thiophenol (74 µl, 0.73 mmol) was added to a solution of 1a (0.20 g, 0.66 mmol) in toluene (4 mL). The reaction mixture was stirred initially at room temperature for 2 h and
then at reflux for 7h. CH₂Cl₂ (10 mL) was added and the organic phase was washed with aqueous NaOH (1 M, 2 × 10 mL), water (10 mL), brine (10 mL), dried and evaporated. Purification by chromatography using ethyl acetate-hexane (5:95) as eluent gave 47a (90 mg, 36%) as a white, crystalline solid; mp 108–110 °C; spectroscopic characteristics are identical to those described previously.¹⁵

Selenium Nucleophiles

**N-(4-Methylphenyl)-Z-3-(phenylseleno)-2-(phenylthio)propenamide 50a**

Sodium borohydride (25 mg, 0.66 mmol) was added portionwise to a stirred solution of diphenyl diselenide (99 mg, 0.33 mmol) in dry ethanol (2 mL). The solution turned colourless indicating the formation of sodium phenylselenide. This solution was transferred by cannula to a stirred solution of 1a (0.20 g, 0.66 mmol) in dry ethanol (3 mL). The reaction was complete by TLC analysis after stirring at room temperature for 16 h and water (10 mL) was then added to quench the excess reagent. The aqueous phase was extracted with CH₂Cl₂ (2 × 10 mL) and the combined organic layers were washed with brine (2 × 20 mL), dried and evaporated. Purification by chromatography using ethyl acetate-hexane (5:95) as eluent gave 50a (0.17 g, 60%) as a light yellow, crystalline solid; mp 86–88 °C; (Found C, 62.50; H, 4.56; N, 3.56; S, 8.01. C₂₂H₁₉NOSSe requires C, 62.26; H, 4.51; N, 3.30; S, 7.55%); νmax/cm⁻¹ (KBr) 3253 (br NH), 1643, 1593 (CO α,β-unsaturated amide); δH (270 MHz, CDCl₃) 2.28 (3H, s, ArCH₃), 7.06-7.64 (9H, m, ArH), 8.69 (1H, br s, NH), 9.04 [1H, s, C(3)H=]; δC (67.8 MHz, CDCl₃) 20.9 (ArCH₃), 119.9 (aromatic CH), 122.7 (aromatic C or SC=), 126.8, 127.4, 128.6, 129.5, 130.1, 131.2 (aromatic CH), 132.9 (aromatic C or SC=), 133.4, 133.5 (aromatic CH), 134.2, 135.1 (aromatic C or SC=), 157.0 [C(3)H=], 160.5 (CO); MS m/z 425 (M⁺, 100%), 377 (21%), 348 (1%, M⁺-Ph), 268 (33%, M⁺-PhSeH), 134 [100%, (PhS=C=CH)⁺].

Acknowledgements

IRCSET, Forbairt, Merck and University College Cork are gratefully acknowledged for funding of this work. The authors wish to thank final year project students M. Brennan,
D. Foley and F. O'Donoghue for input on some aspects of this work. Rigaku are acknowledged for crystal structure determination of 24a.


28. Rajappa et al. have reported that the chemical shift of an enamine proton which is hydrogen bonded to oxygen is shifted downfield relative to the non-hydrogen bonded proton (A.N. Dixit, K.V. Reddy, A.R. Deshmukh, S. Rajappa, B. Ganguly, J. Chandrasekhar, Tetrahedron, 1995, 51, 1437)


