A novel synthesis of didehydroamino acid esters from azomethine ylides

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A novel synthesis of didehydroamino acid (DDAA) esters 5 is described, starting from aldimines 2. The mechanism for this reaction has been shown to involve the cycloaddition of an azomethine ylide 3 to an imine 2, followed by the base-catalysed ring-opening of the resulting imidazolidine intermediate 7. This novel method has also been extended to the synthesis of DDAA esters 5 catalysed by imines.

The synthesis of biologically active amino acids and peptides is of continuing interest and, in particular, the synthesis of α,β-didehydroamino acids (DDAAs) has recently received increased attention with regard to the preparation of biologically active compounds.[1] For example, the enantioselective hydrogenation of DDAAs has frequently been employed for the synthesis of complex non-ribosomal amino acids;[2] DDAAs themselves play a very important role in nature in the biosynthesis of some amino acids,[3] and a number of DDAAs have been found in natural products having antimicrobial activity.[4] Due to their importance, numerous methods have been developed for the synthesis of DDAAs.[5]

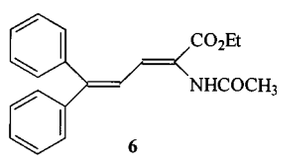
We wish to report here a novel, simple, and mild preparative route to DDAA esters starting from simple aldimines. In this full account[6] we survey the scope, limitations and mechanism of this new method.

Results and discussion

Our initial studies were designed to explore the 1,5- or 1,7-electrocyclizations of azomethine ylides with α,β,γ,δ-unsaturation **3a**–**d**, for comparison with the previously studied nitrile ylides.[7] The dipoles **3a**–**e** were generated by the 1,2-prototropy[8] of the corresponding aldimines **2a**–**e**, which are themselves easily generated *via* the condensation of glycine esters with aldehydes **1a**–**c** (Scheme 1). 3,3-Bis(4-chlorophenyl)propenal **1b** was prepared from 4,4-dichlorobenzophenone using the method of Nagata *et al.*[9]

Upon refluxing a solution of the imines **2a**–**e** and triethylamine in toluene the azomethine ylides **3a**–**e** were generated and this was confirmed by the trapping of ylide **3a** with *N*-phenylmaleimide (Scheme 1). The stereochemistry of the cycloadducts **4a**–**c** was established by NOE experiments, and by X-ray crystallography of cycloadduct **4a** (Fig. 1).

However, in the absence of the trapping agent, the azomethine ylides **3a**–**e**, again generated under the same conditions, undergo a novel transformation to the dehydroamino acid esters **5a**–**e** (Scheme 1, Table 1). The stereochemistry of the dehydroamino acid esters was again confirmed by NOE experiments, and by X-ray crystallography of the *N*-acetyl derivative **6** prepared from **5a** (Fig. 2). Generation of the azomethine ylides by treatment of the imines with acetic acid (method 2) or by photolysis (method 3) also led to the formation of the DDAA esters (Table 1).



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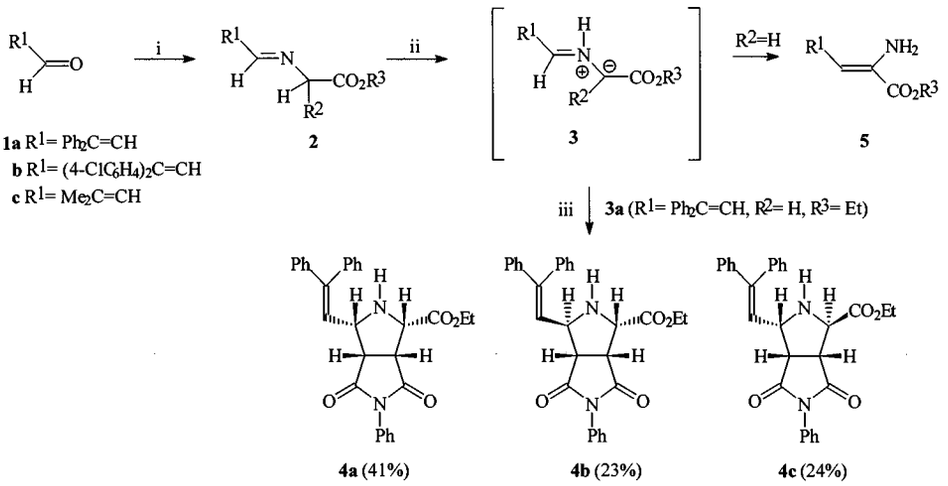
In order to establish the mechanism for this reaction, we initially performed a crossover experiment by heating a mixture of imines **2b** and **2c** in dry toluene. A mixture of all four possible DDAA esters **5a**–**d** was obtained. In addition, a mixture of the dehydroamino acid esters **5b** and **5c** was unchanged under these conditions. These results suggested that the DDAA esters are formed *via* an intermolecular reaction, presumably involving the initial cycloaddition of an azomethine ylide **3** to the precursor imine **2**. Ring-opening of the resulting imidazolidine **7** would then give the DDAA ester **5** (Scheme 2). The first step in this process—the generation of azomethine ylides from imines—is a well established process[10] and this 1,2-prototropy is a function of the basicity of the imino nitrogen atom and the pK_a of the azaallylic proton[11]—properties which are influenced by the nature of substituents. It has been shown that both acids (Brønsted or Lewis) and bases catalyse this 1,2-prototropy effectively.[12]

Only a few examples of the second step—the cycloaddition of an azomethine ylide to an imine—have been reported. Grigg and co-workers reported the dimerisation of imines **2f**,**g** in the presence of various metal salts (*e.g.* $ZnBr_2$, $MgClO_4$, and $CoCl_2$). In order to further confirm this mechanism, our next aim was to isolate this proposed imidazolidine intermediate. Thus, when we treated the acetonitrile solution of imine **2i** with $MgClO_4$ at room temperature, the *syn-exo* **7i** and *syn-endo* **7i′** cycloadducts ("dimer imines") were formed (in a 3:1 ratio by ^{1}H NMR spectroscopy) (Scheme 2). The two isomers were separated by column chromatography and their stereochemistry deduced by comparison of the coupling constants for the doublets for H-4 and H-5 with the values for similar compounds prepared by Grigg *et al.* (Table 2).[13] The reaction of the mixture of imine dimers **7i**,**i′** with DBU at room temperature led to a single isomer of the didehydroamino acid ester **5i**



a R^1= Ph_2C=CH, R^2= H, R^3= Et
b R^1= Ph_2C=CH, R^2= H, R^3= Me
c R^1= $(4\text{-}ClC_6H_4)_2C$=CH, R^2= H, R^3= Et
d R^1= $(4\text{-}ClC_6H_4)_2C$=CH, R^2= H, R^3= Me
e R^1= Me_2C=CH, R^2= H, R^3=Et
f R^1=2-naphthyl, R^2= H, R^3= Me
g R^1= Ph, R^2= CO_2Me, R^3= Me
h R^1= $4\text{-}O_2NC_6H_4$, R^2= H, R^3= Et
i R^1= $3\text{-}O_2NC_6H_4$, R^2= H, R^3= Et
j R^1= Ph, R^2= H, R^3= Me
k R^1= $4\text{-}MeOC_6H_4$, R^2= H, R^3= Et
l R^1= $4\text{-}FC_6H_4$, R^2= H, R^3= Et
m R^1= $4\text{-}ClC_6H_4$, R^2= H, R^3= Et
n R^1= Ph_2C=CH, R^2= CH_2Ph, R^3= Et

Scheme 1 *Reagents and conditions*: i, $H_2NCHR^2CO_2R^3$, $PhCH_3$, Et_3N, reflux; ii, $PhCH_3$, Et_3N, reflux; iii, $PhCH_3$, *N*-phenylmaleimide, Et_3N, reflux

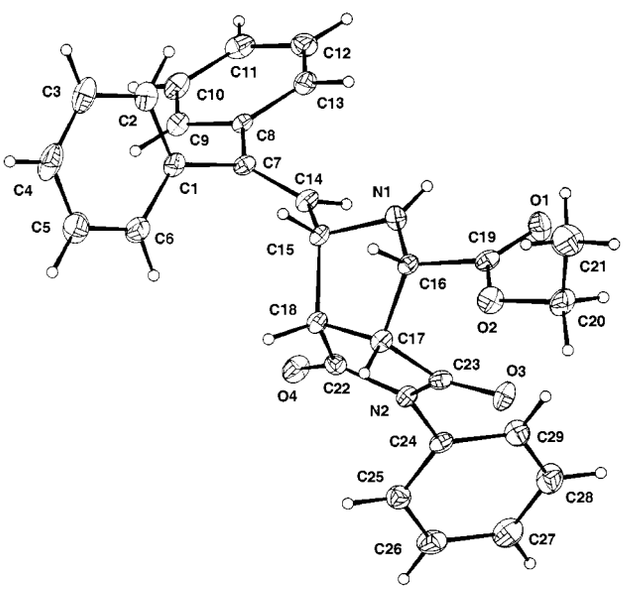


Fig. 1 Crystal structure of cycloadduct **4a**

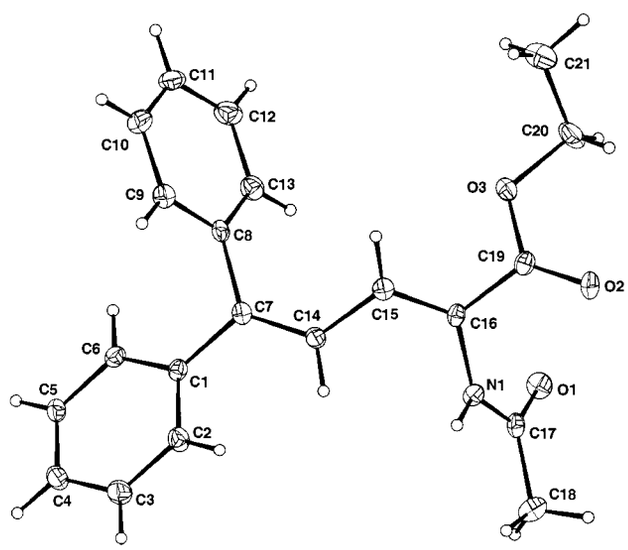


Fig. 2 Crystal structure of didehydroamino acid ester derivative **6**

along with decomposition products—as observed in the one pot reaction. Further evidence for this mechanism was obtained from the reaction of the phenylalanine derivative under the standard conditions. Although the corresponding azomethine ylide **3n** could be trapped with *N*-phenylmaleimide to give the cycloadduct **8** (Scheme 3), no didehydroamino acid ester was obtained in the absence of trapping agent. This is presumably because the corresponding imidazolidine **7n** (R^1 = Ph_2C=CH, R^2 = CH_2Ph, R^3 = Et) has no proton on the α-carbon (derived from the amino acid) and thus cannot ring-open *via* the mechanism shown.

Cerecetto *et al.* have reported a similar preparation of DDAAs from the condensation of glycine esters with nitro-substituted heterocyclic aldehydes, *e.g.* **9**.[14] These workers propose that the dehydroamino acids **12** are formed *via* the condensation of the imine anion **10** with a second molecule of aldehyde (or imine), followed by hydrolysis of the imine **11** (Scheme 4). We have repeated this work both in the presence and absence of *N*-phenylmaleimide (as a trapping agent). In the absence of trapping agent the dehydroamino acid ester **12** is formed, whilst in the presence of trapping agent both DDAA ester **12** and the product **14**, from the cycloaddition of azomethine ylide **13** to *N*-phenylmaleimide, are obtained, thus suggesting the intermediacy of the azomethine ylide in this process.

With the exception of their decomposition by thermal retrocycloaddition, no attempt has been made to explore the chemistry of the imidazolidines.[13] We have found that the *syn-exo* imidazolidine **7i** is stable under acidic conditions (trifluoroacetic acid, 60 °C, $CDCl_3$) but that the reaction of **7i** with DDQ gives the Δ^2-imidazoline **15** (Scheme 5).

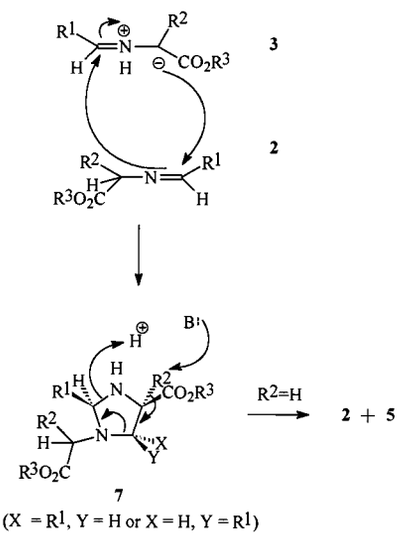
With regard to this proposed mechanism we performed the next series of experiments on electron-poor imine derivatives. Imines **2h**,**i**, when treated with one equivalent of DBU in

Table 1 Yields and conditions for preparation of DDAA esters **5**

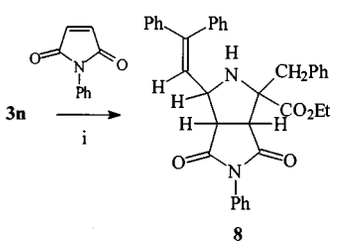
Entry	Imine **2**	DDAA ester **5**	Yield (%)	Reaction conditions
1	**2a** (R^1 = Ph_2C=CH, R^2 = H, R^3 = Et)	**5a**	75	$PhCH_3/Et_3N$/reflux
2	**2a** (R^1 = Ph_2C=CH, R^2 = H, R^3 = Et)	**5a**	81	$PhCH_3/Et_3N$/reflux, then AcOH
3	**2a** (R^1 = Ph_2C=CH, R^2 = H, R^3 = Et)	**5a**	61	*hν*, EtOH
4	**2b** (R^1 = Ph_2C=CH, R^2 = H, R^3 = Me)	**5b**	67	$PhCH_3/Et_3N$/reflux
5	**2c** [R^1 = $(4\text{-}ClC_6H_4)_2C$=CH, R^2 = H, R^3 = Et]	**5c**	62	$PhCH_3/Et_3N$/reflux
6	**2e** (R^1 = Me_2C=CH, R^2 = H, R^3 = Et)	**5e**	22	THF/Et_3N, then DBU/LiBr/MeCN/r.t.
7	**2h** (R^1 = 4-NO_2, R^2 = H, R^3 = Et)	**5h**	60	DBU/MeCN/r.t.
8	**2i** (R^1 = 3-NO_2, R^2 = H, R^3 = Et)	**5i**	55	DBU/MeCN/r.t.

Table 2 ^{1}H NMR chemical shifts and coupling constants for imidazolidines **7f**,**i**

Entry	X	Y	δ(H-4)	δ(H-5)	$J_{4,5}$/Hz
syn-exo **7f**	R^1 (2-naphthyl)	H	4.12	4.75	6.5
syn-endo **7f′**	H	R^1 (2-naphthyl)	4.54	4.94	9.3
syn-exo **7i**	R^1 (3-nitrophenyl)	H	3.87	4.62	6.6
syn-endo **7i′**	H	R^1 (3-nitrophenyl)	4.50	4.87	9.0



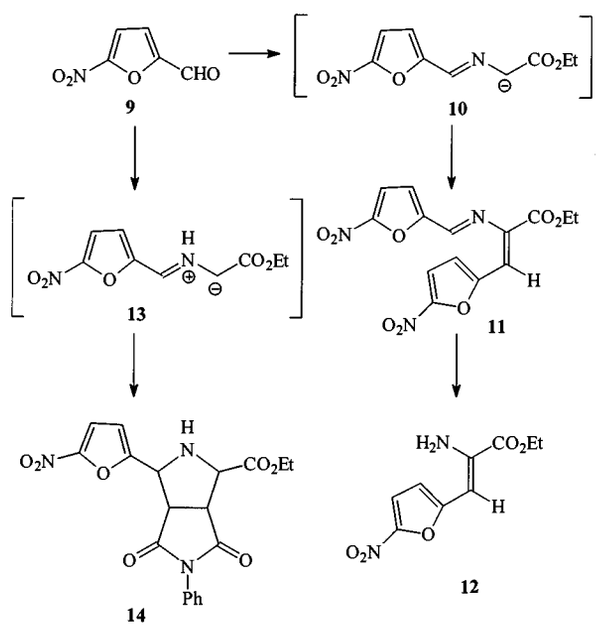
Scheme 2



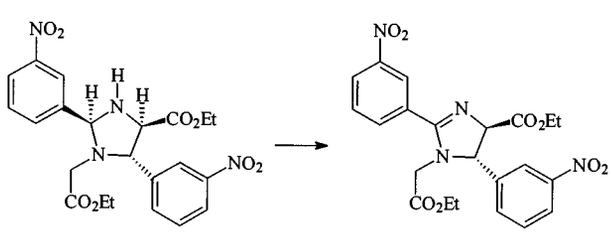
Scheme 3 *Reagents and conditions*: i, $PhCH_3$, Et_3N, reflux

acetonitrile solution, gave the corresponding DDAA derivatives. The pure DDAAs **5h**,**i** were isolated, after purification by flash chromatography, in 40–60% yield. No reaction was observed at below 0 °C or upon changing the base to triethylamine or DABCO (at room temperature). There was also no reaction when a catalytic amount of DBU (5–10%) was employed. For example, when the imine **2i** was treated with DBU in the presence of *N*-phenylmaleimide and lithium bromide, no didehydroamino acid ester **5i** was obtained, but it was possible to isolate a single diastereomer of cycloadduct **16**, which arises from the *syn*-azomethine ylide through an *endo* transition state.[14,15] The stereochemistry of the cycloadduct was assigned by comparison with previous work. No reaction occurred with the imines **2j**–**m** even in the presence of other metal salts ($ZnBr_2$, $CoCl_2$).

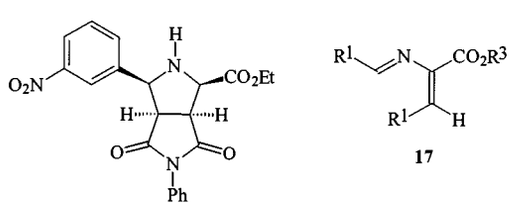
Our understanding of the intermolecular nature of the mechanism for this reaction suggested the possibility of the



Scheme 4



Scheme 5 *Reagents and conditions*: DDQ, $PhCH_3$, reflux, 12 h, 71%



imine-catalysed synthesis of DDAA esters. This was therefore investigated for the imines **2j**–**m** for which the standard conditions had been unsuccessful. The most suitable imines were **2a**,**b** and **i**, which were used in a catalytic amount (5 mol%), in a

Table 3 Data for catalytic formation of didehydroamino acid esters **5**

Entry	Imine **2**	**2** δ(CH=N)	**5** δ(CH=)	**17** δ(CH=)	Time/days	Catalyst	Yield (%) **5**	Yield (%) **17**
1	**j** (R^1 = Ph, R^2 = H, R^3 = Me)	8.30	6.41	8.57	5	**2b**	34[a]	27[a]
2	**k** (R^1 = 4-$MeOC_6H_4$, R^2 = H, R^3 = Et)	8.21	6.48	8.53	7	**2a**	19[b]	19[b]
3	**k** (R^1 = 4-$MeOC_6H_4$, R^2 = H, R^3 = Et)	8.21	6.48	8.53	13	**2a**	36[b] (15[a])	26[b]
4	**l** (R^1 = 4-FC_6H_4, R^2 = H, R^3 = Et)	8.26	6.43	8.59	6	**2a**	20[b]	29[b]
5	**l** (R^1 = 4-FC_6H_4, R^2 = H, R^3 = Et)	8.26	6.43	8.59	9	**2a**	33[b]	25[b] (18[a])
6	**m** (R^1 = 4-ClC_6H_4, R^2 = H, R^3 = Et)	8.25	6.41	8.59	6	**2a**	41[b]	29[b]
7	**m** (R^1 = 4-ClC_6H_4, R^2 = H, R^3 = Et)	8.25	6.41	8.59	9	**2a**	49[b] (35[a])	25[b]
8	**m** (R^1 = 4-ClC_6H_4, R^2 = H, R^3 = Et)	8.25	6.41	8.59	5	**2i**	25[b]	17[b]
9	**m** (R^1 = 4-ClC_6H_4, R^2 = H, R^3 = Et)	8.25	6.41	8.59	9	**2a**	25[b]	17[b]

[a] Isolated yield. [b] Yield based on ^{1}H NMR spectrum.

refluxing toluene solution of imines **2j**–**m**. The dehydroamino acid esters **5** were obtained in low to moderate yield (Table 3). The reactions were easily monitored by ^{1}H NMR spectroscopy and singlet peaks were observed for all the main components of the reaction mixture, including the intermediate dimer and one more unexpected product. In spite of all efforts to avoid any moisture in the reaction mixture, some slow decomposition of the imines **2** was observed (slowly growing singlet for the aldehyde at δ 9.0) over the longer reflux times employed. Under these reaction conditions the aldehydes then reacted with the dehydroamino acid ester to form the imine **17** (singlet for the CH=N around δ 8.5). This side reaction considerably decreased the yield of the DDAAs and caused additional difficulties during the column chromatography.

As can be seen from Tables 1 and 3, the substituents on the aromatic ring and/or the imine double bond have a significant effect on the conversion of the imines; a *p*-methoxy group (**2k**) decreases the yield, while the presence of halogens or electron withdrawing substituents (**2h**,**i**,**l**,**m**) favours the reaction. In addition, the yields of **17** are always comparable with the yield of DDAA **5**.

Experimental

Mps were determined on a Gallenkamp apparatus and are uncorrected. Elemental analyses were performed on a Perkin-Elmer 240C or Carlo Erba 1106 Elemental Analyser. IR spectra were recorded on a Perkin-Elmer 1600 series FTIR or Unicam research series FTIR spectrophotometer using sodium chloride plates. ^{1}H NMR spectra were acquired on a Bruker WM360 spectrometer at 360 MHz, or on a JEOL GSX 270 FT NMR at 270 MHz. Coupling constants (J) are given in Hz and all chemical shifts are relative to an internal standard of tetramethylsilane. ^{13}C NMR spectra were obtained on the Bruker WM360 (90 MHz) and JEOL GFX 270 FT NMR (68 MHz) spectrometers. Low resolution electron impact mass spectra were obtained on a Fisons VG Platform II or Trio 2000 VG. High resolution spectra were obtained on a VG ZAB-E spectrometer (EPSRC Mass Spectrometry Service Centre, Swansea). Thin layer chromatography was performed on Merck silica gel $60F_{254}$. All solvents were purified according to standard procedures.[17] Diethyl ether and tetrahydrofuran were freshly distilled over sodium wire with a trace of benzophenone. Toluene was distilled from, and stored over, sodium wire. Fisons silica gel 60 (35–70 micron) was used for wet flash chromatography. The samples were applied in liquid form or were pre-adsorbed onto silica 60 (35–70 micron) from dichloromethane solutions. Imines **2j**,[18] **2k**[19] and **2m**,[20] and imidazolidines **7f**,**f′**[13] were prepared as described previously.

Crystal data for *N*-acetyldehydroamino acid ester 6

$C_{21}H_{21}NO_3$, M = 335.39. Orthorhombic, a = 19.066(2), b = 9.503(2), c = 20.204(4) Å, (by least squares refinement of the setting angles for 250 reflections with θ = 2.02–25.02°), V = 3660.6(11) Å^3, space group *Pbca* (No. 61), Z = 8, D_m = 1.217 g cm^{-3}. F(000) = 1424. White crystals. Crystal dimensions 0.24 × 0.15 × 0.10 mm, μ(Mo-Kα) = 0.81 cm^{-1}.

Data collection and processing. FAST TV Area detector diffractometer following previously described procedures.[21] From the ranges scanned, 12 198 data were collected ($2.02 \leqslant \theta \leqslant 25.02°$), 2876 unique ($R_{int}$ = 0.1089).

Structural analysis and refinement. The structure was solved *via* direct methods (SHELX-S)[22] and refined on F_o^2 by full-matrix least-squares (SHELXL-93)[23] using all unique data corrected for Lorentz and polarisation factors to final wR (on F_o^2) and R (on F) values of 0.0703 and 0.0699 for 228 parameters (non-hydrogen atoms anisotropic; hydrogens in idealised positions with U_{iso}s tied to the U_{eq}s of the parents). The corresponding R-values for 1780 data with $I > 2\sigma(I)$ are 0.0655 and 0.0351, respectively. The weighting scheme used was $w = 1/[\sigma^2(F_o^2) + (0.0024P)^2]$, where $P = [\max(F_o)^2 + 2(F_c)^2]/3$; this gave satisfactory agreement analyses. Sources of scattering factors as in ref. 23.†

Crystal data for cycloadduct 4a

$C_{29}H_{26}N_2O_4$, M = 466.52. Monoclinic, a = 10.712(2), b = 19.428(7), c = 11.8653(5) Å, β = 102.300(8)° (by least squares refinement of the setting angles for 250 reflections within θ = 1.76–24.91°), V = 2412.4(10) Å^3, space group $P2_1/a$ (a non-standard setting of $P2_1/c$ No. 14), Z = 4, D_m = 1.284 g cm^{-3}. F(000) = 984. White crystals. Crystal dimensions 0.22 × 0.20 × 0.26 mm, μ(Mo-Kα) = 0.86 cm^{-1}.

Data collection and processing. FAST TV Area detector diffractometer following previously described procedures.[21] From the ranges scanned, 9701 data were collected ($1.76 \leqslant \theta \leqslant 24.91°$), 3569 unique ($R_{int}$ = 0.0791).

Structural analysis and refinement. The structure was solved *via* direct methods (SHELX-S)[22] and refined on F_o^2 by full-matrix least-squares (SHELXL-93)[23] using all unique data corrected for Lorentz and polarisation factors to final wR (on F_o^2) and R (on F) values of 0.0979 and 0.0828 for 317 parameters (non-hydrogen atoms anisotropic; hydrogens in idealised positions with U_{iso}s tied to the U_{eq}s of the parents). The corresponding R-values for 2069 data with $I > 2\sigma(I)$ are 0.0921 and 0.0447, respectively. The weighting scheme used was $w = 1/[\sigma^2(F_o^2) + (0.0251P)^2]$, where $P = [\max(F_o)^2 + 2(F_c)^2]/3$; this gave satisfactory agreement analyses.

3,3-Bis(4-chlorophenyl)prop-2-enal 1b

In an oven-dried two-necked flask was placed sodium hydride (0.106 g, 4.42 mmol, 60% oil dispersion), which was washed with dry THF (5 cm^3). THF (2 cm^3) was added, followed by a solution of diethyl 2-(cyclohexylamino)vinylphosphonate[24]

† Full crystallographic details, excluding structure factor tables, have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 1*, available *via* the RSC Web page (http://www.rsc.org/authors). Any request to the CCDC for this material should quote the full literature citation and the reference number 207/238.

(1.1553 g, 4.42 mmol) in dry THF (2 cm^3), with stirring, over 10 min, at 0–5 °C. The mixture was stirred for an additional 10 min at 0–5 °C to ensure complete reaction. A solution of 4,4-dichlorobenzophenone (0.55 g, 2.21 mmol) in dry THF (8 cm^3) was added dropwise to the mixture over *ca*. 15 min, ensuring that the temperature did not exceed 5 °C. The mixture was stirred for 2 h before pouring into water (50 cm^3), and extracting with diethyl ether (3 × 30 cm^3). The combined organic extracts were washed with brine (2 × 20 cm^3), dried (Na_2SO_4), and evaporated under reduced pressure at 25–30 °C. The residue was dissolved in benzene (10 cm^3) and transferred to a flask fitted with a condenser. Oxalic acid dihydrate (2.74 g, 21.7 mmol) in water (35 cm^3) was added to the reaction mixture, which was then refluxed for 2 h, with stirring under N_2. The organic layer was separated and the aqueous phase extracted with diethyl ether (3 × 30 cm^3). The combined organic extracts were washed with water (30 cm^3) and brine (30 cm^3), dried (Na_2SO_4) and concentrated under reduced pressure to give **1b** as a yellow oil (0.327 g, 54%) (Found: M^+, 276.011. Calc. for $C_{15}H_{10}Cl_2O$: *M*, 276.011); ν_{max}(liquid film)/cm^{-1} 3050 (CH), 2985 (CH), 1672 (C=O), 1598 (C=C); δ_H(270 MHz, $CDCl_3$) 6.49 (1H, d, *J* 7.9, C=CH, 7.15–7.40 (8H, m, Ar-H), 9.45 (1H, d, *J* 7.9, CH=O); δ_C(68 MHz, $CDCl_3$) 127.9 (CH), 128.7 (CH), 128.8 (CH), 128.9 (CH), 129.8 (CH), 132.9 (quat.), 134.5 (quat.), 135.4 (quat.), 135.9 (quat.), 192.5 (quat., C=O); *m*/*z* 280/278/276 (M^+, 6/32/53%), 241 (100), 212 (22), 136 (33).

Preparation of imines

***N*-(Ethoxycarbonylmethyl)-3,3-diphenylprop-2-enimine 2a**

β-Phenylcinnamaldehyde (0.20 g, 0.96 mmol) and glycine ethyl ester hydrochloride (0.13 g, 0.96 mmol) were dissolved in toluene (6 cm^3), and triethylamine (0.10 g, 0.13 cm^3, 0.96 mmol) was added. The mixture was refluxed, with continuous removal of water using a Dean–Stark trap, for 4 h. The triethylamine hydrochloride was filtered off and the solvent evaporated under reduced pressure to give N-(*ethoxycarbonylmethyl*)-3,3-*diphenylprop*-2-*enimine* **2a** as a brown oil (0.22 g, 79%) (Found: M^+, 293.141. Calc. for $C_{19}H_{19}NO_2$: *M* = 293.141); ν_{max}(liquid film)/cm^{-1} 2980 (CH), 1731 (C=O), 1681 (C=N), 1622 (C=C); δ_H(360 MHz, $CDCl_3$) 1.29 (3H, t, *J* 7.1, CH_3), 4.16 (2H, s, CH_2, 4.19 (2H, q, *J* 7.1, CH_2), 6.94 (1H, d, *J* 9.2, C=CH), 7.16–7.41 (10H, m, Ar-H), 7.86 (1H, d, *J* 9.1, CH=N); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 60.9 (CH_2), 61.9 (CH_2), 125.2 (CH), 127.2 (CH), 127.5 (CH), 127.9 (CH), 128.1 (CH), 128.2 (CH), 128.3 (CH), 138.1 (quat.), 138.8 (CH), 140.5 (quat.), 141.3 (quat.), 165.3 (quat., C=O); *m*/*z* 293 (M^+, 16%), 264 (61), 220 (17), 206 (100).

Also prepared by the same method were:

***N*-(Methoxycarbonylmethyl)-3,3-diphenylprop-2-enimine 2b.** Deep yellow oil (0.23 g, 86%) (Found: M^+, 279.125. Calc. for $C_{18}H_{17}NO_2$: *M*, 279.125); ν_{max}(liquid film)/cm^{-1} 2984 (CH), 1729 (C=O), 1679 (C=N), 1610 (C=C); δ_H(270 MHz, $CDCl_3$) 3.72 (3H, s, CH_3), 4.21 (2H, s, CH_2), 6.93 (1H, d, *J* 9.0, C=CH), 7.12–7.40 (10H, m, Ar-H), 7.87 (1H, d, *J* 9.1, CH=N); *m*/*z* 279 (M^+, 33%), 264 (100), 220 (29).

***N*-(Ethoxycarbonylmethyl)-3,3-bis(4-chlorophenyl)prop-2-enimine 2c.** 3,3-Bis(4-chlorophenyl)prop-2-enal **1b** (0.327 g, 1.18 mmol), glycine ethyl ester hydrochloride (0.16 g, 1.18 mmol) and triethylamine (0.12 g, 0.16 cm^3, 1.18 mmol) were dissolved in toluene (8 cm^3) and reacted as for **2a** to give the title compound **2c** as a deep yellow oil (0.359 g, 84%) (Found: M^+, 361.063. Calc. for $C_{19}H_{17}Cl_2NO_2$: *M*, 361.063); ν_{max}(liquid film)/cm^{-1} 1735 (C=O), 1652 (C=N), 1587 (C=C); δ_H(270 MHz, $CDCl_3$) 1.20 (3H, t, *J* 6.9, CH_3), 4.12 (2H, s, CH_2), 4.13 (2H, q, *J* 6.9, CH_2), 6.82 (1H, d, *J* 9.2, C=CH), 7.10–7.38 (8H, m, Ar-H), 7.74 (1H, d, *J* 9.3, CH=N); δ_C(68 MHz, $CDCl_3$) 14.2 (CH_3), 61.2 (CH_2), 61.8 (CH_2), 124.9 (CH), 126.7 (CH), 127.3 (CH), 128.5 (CH), 129.3 (CH), 139.5 (quat.), 140.1 (CH), 140.8 (quat.), 141.4 (quat.), 167.1 (quat., C=O); *m*/*z* 365/363/361 (M^+, 4/12/27%), 332 (38), 288 (28), 274 (100).

***N*-(Ethoxycarbonylmethyl)-4-nitrophenylmethanimine 2h.** Yellow oil (1.01 g, 97%) (Found: MH^+, 237.087. Calc. for $C_{11}H_{13}N_2O_4$: MH^+, 237.087); ν_{max}(liquid film)/cm^{-1} 3070 (CH), 2985 (CH), 2908 (CH), 1735 (C=O), 1646 (C=N), 1600 (C=C), 1519 and 1346 (NO_2); δ_H(270 MHz, $CDCl_3$) 1.33 (3H, t, *J* 7.3, CH_3), 4.26 (2H, q, *J* 7.3, CH_2), 4.48 (2H, s, CH_2), 7.96 (2H, d, *J* 8.6, Ar-2′, 6′H), 8.27 (2H, d, *J* 8.6, Ar-3′, 5′H), 8.40 (1H, s, CH=N); δ_C(68 MHz, $CDCl_3$) 13.6 (CH_3), 60.8 (CH_2), 61.3 (CH_2), 123.3 (2 × CH), 128.6 (2 × CH), 140.4 (quat.), 148.8 (quat.), 162.5 (CH), 169.0 (quat., C=O); *m*/*z* 237 (MH^+, 100%), 207 (83), 191 (20), 179 (22), 163 (99), 177 (47), 88 (50), 70 (20).

***N*-(Ethoxycarbonylmethyl)-3-nitrophenylmethanimine 2i.** Yellow solid (1.01 g, 96%), mp 49–50 °C (Found: MH^+, 237.087. Calc. for $C_{11}H_{13}N_2O_4$: MH^+, 237.087); ν_{max}(liquid film)/cm^{-1} 3085 (CH), 2995 (CH), 2935 (CH), 2877 (CH), 1739 (C=O), 1650 (C=N), 1531 and 1349 (NO_2); δ_H(270 MHz, $CDCl_3$), 1.35 (3H, t, *J* 7.3, CH_3), 4.26 (2H, q, *J* 7.3, CH_2), 4.47 (2H, s, CH_2), 7.62 (1H, t, *J* 7.9, Ar-5′H), 8.15 (1H, d, *J* 7.9, Ar-6′H), 8.29 (1H, dd, *J* 8.6, 2.6, Ar-4′H), 8.39 (1H, s, CH=N), 8.61 (1H, d, *J* 2, Ar-2′H); δ_C(68 MHz, $CDCl_3$) 14.6 (CH_3), 61.7 (CH_2), 62.1 (CH_2), 123.7 (CH), 126.0 (CH), 130.1 (CH), 134.3 (CH), 137.7 (quat.), 149.0 (quat.), 163.2 (CH), 170.8 (quat., C=O); *m*/*z* 237 (MH^+, 32%), 207 (97), 179 (53), 163 (100), 146 (59), 117 (93), 104 (33), 90 (81), 88 (83), 78 (60).

***N*-(Ethoxycarbonylmethyl)-3-methylbut-2-enimine 2e**

In an oven-dried flask, 3-methylbut-2-enal (0.30 g, 0.34 cm^3, 3.57 mmol) was added to a suspension of glycine ethyl ester hydrochloride (0.37 g, 2.65 mmol) and triethylamine (0.27 g, 0.37 cm^3, 2.65 mmol) in dry THF (8 cm^3), at −20 °C, with stirring under N_2. After stirring at −20 °C, for 2 h, the reaction mixture was allowed to stand at this temperature for 1 h. Na_2CO_3 (2 g) was added and the mixture was stirred for a further 2 h, at −20 °C. The triethylamine hydrochloride was filtered off and the solvent concentrated under reduced pressure, to give the title compound **2e** as a brown oil (0.49 g, 82%) (Found: M^+, 169.110. Calc. for $C_9H_{15}NO_2$: *M*, 169.110); ν_{max}(liquid film)/cm^{-1} 2977 (CH), 2911 (CH), 1739 (C=O), 1650 (C=N), 1619 (C=C); δ_H(400 MHz, $CDCl_3$) 1.3 (3H, t, *J* 7.1, CH_3), 1.89 (3H, s, CH_3), 1.94 (3H, s, CH_3), 4.16 (2H, q, *J* 7.2, CH_2), 4.23 (2H, s, CH_2), 6.08 (1H, d, *J* 9.4, C=CH), 8.2 (1H, d, *J* 9.4, CH=N); δ_C(68 MHz, $CDCl_3$) 13.0 (CH_3), 18.6 (CH_3), 26.3 (CH_3), 60.6 (CH_2), 61.9 (CH_2), 125.0 (CH), 148.2 (quat.), 163.1 (CH), 170.1 (quat., C=O); *m*/*z* 169 (M^+, 100%), 154 (33), 142 (58).

***N*-(Ethoxycarbonylmethyl)-4-fluorophenylmethanimine 2l**

To a stirred suspension of glycine ethyl ester hydrochloride (0.4 g, 2.88 mmol), triethylamine (0.29 g, 0.44 ml, 2.88 mmol) in DCM (20 ml), was added 4-fluorobenzaldehyde (0.35 g, 0.3 ml, 2.88 mmol) and anhydrous magnesium sulfate (*ca*. 2 g) after 10 min. The mixture was stirred overnight. After filtration the solution was evaporated under reduced pressure to give N-(*ethoxycarbonylmethyl*)-4-*fluorophenylmethanimine* **2l** as a colourless oil (0.57 g, 97%) (Found: MH^+, 210.093. Calc. for $C_{11}H_{13}FNO_2$: MH^+, 210.093); ν_{max}(liquid film)/cm^{-1} 2985 (CH), 2877 (CH), 1743 (C=O), 1646 (C=N), 1610 (C=C); δ_H(270 MHz, $CDCl_3$) 1.31 (3H, t, *J* 7.3, CH_3), 4.24 (2H, q, *J* 7.3, CH_2), 4.39 (2H, s, CH_2), 7.10 (2H, t, *J* 9.0, Ar-3′, 5′H), 7.78 (2H, dd, *J* 9.0, 5.9, Ar-2′, 6′H), 8.26 (1H, s, CH=N); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 61.1 (CH_2), 61.9 (CH_2), 115.7 (*J* 21.8, 2 × CH), 130.4 (*J* 8.3, 2 × CH), 131.9 (quat.), 132.7 (quat.), 162.7 (CH), 170.1 (quat., C=O); *m*/*z* 210 (MH^+, 19%), 180 (50), 136 (97), 123 (16), 109 (100).

Generation and reactions of azomethine ylides

3,3-Diphenylprop-2-eniminium ethoxycarbonylmethyl ylide 3a

Trapping of 3,3-diphenylprop-2-eniminium ethoxycarbonylmethyl ylide 3a with *N*-phenylmaleimide. β-Phenylcinnamalde-

hyde (0.10 g, 0.48 mmol) and glycine ethyl ester (0.07 g, 0.48 mmol) were dissolved in toluene (6 cm^3), with stirring, and triethylamine (0.05 g, 0.07 cm^3, 0.48 mmol) was added. The mixture was refluxed with the continuous removal of water, using a Dean–Stark trap, for 4 h. The triethylamine hydrochloride was filtered off and *N*-phenylmaleimide (0.06 g, 0.36 mmol) was added. The mixture was refluxed for a further 3 h. After cooling, the solvent was evaporated under reduced pressure to give a pale brown oil (0.17 g, 77%). The reaction afforded a mixture of products by TLC. The pale brown oil was purified by column chromatography on silica, eluting with ethyl acetate–light petroleum (40–60 °C) (0:100 to 30:70), to give two fractions. Fraction one gave a murky white solid (0.11 g, 65%). Spectroscopic analysis showed the presence of three isomers. Recrystallisation from ethyl acetate–light petroleum (40–60 °C) (30:70) gave **4a** as a white crystalline solid (0.07 g, 41%), mp 180–181 °C for one isomer (Found: C, 74.4; H, 5.7; N, 5.9. $C_{29}H_{26}N_2O_4$ requires C, 74.6; H, 5.6; N, 6.0%); ν_{max}(liquid film)/cm^{-1} 2956 (CH), 1738 (C=O), 1709 (C=O), 1594 (C=C); δ_H(360 MHz, $CDCl_3$) 1.25 (3H, t, *J* 7.1, CH_3), 3.30 (1H, t, *J* 7.9, H-2a), 3.57 (1H, t, *J* 7.8, H-5a), 3.88 (1H, d, *J* 7.7, H-5), 3.90 (1H, dd, *J* 9.5, 7.9, H-3), 4.30 (2H, q, *J* 7.1, CH_2), 6.07 (1H, d, *J* 9.5, C=CH), 7.23–7.45 (15H, m, Ar-H); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 49.2 (CH), 50.1 (CH), 60.1 (CH), 62.8 (CH_2), 63.1 (CH), 123.9 (CH), 126.5 (CH), 127.8 (CH), 127.9 (CH), 128.0 (CH), 128.1 (CH), 128.2 (CH), 128.4 (CH), 128.6 (CH), 130.1 (CH), 130.2 (CH), 139.6 (quat.), 141.5 (quat.), 146.3 (quat.), 169.9 (quat.), 175.0 (quat., C=O), 188.1 (quat., C=O), 232.2 (quat., C=O); *m*/*z* 466 (M^+, 100%), 437 (5), 393 (72), 293 (61).

A pale yellow oil (0.04 g, 23%) was obtained for isomer **4b**; ν_{max}(liquid film)/cm^{-1} 2944 (CH), 1733 (C=O), 1701 (C=O), 1590 (C=C); δ_H(360 MHz, $CDCl_3$) 1.27 (3H, t, *J* 7.2, CH_3), 3.45 (1H, dd, *J* 8.3, 2.1, H-2a), 3.78 (1H, t, *J* 8.3, H-5a), 4.25 (2H, q, *J* 7.2, CH_2), 4.45 (1H, d, *J* 8.3, H-5), 4.61 (1H, dd, *J* 9.6, 2.1, H-3), 6.07 (1H, d, *J* 9.6, C=CH), 7.22–7.43 (15H, m, Ar-H); *m*/*z* 466 (M^+, 100%), 393 (44), 293 (98).

Fraction two gave **4c** as a pale yellow oil (0.04 g, 24%), ν_{max}(liquid film)/cm^{-1} 1727 (C=O), 1699 (C=O), 1590 (C=C); δ_H(360 MHz, $CDCl_3$) 1.23 (3H, t, *J* 7.2, CH_3), 3.16 (1H, t, *J* 7.8, H-2a), 3.77 (1H, d, *J* 7.8, H-5a), 4.03 (1H, dd, *J* 9.4, 7.8, H-3), 4.07 (2H, q, *J* 7.2, CH_2), 4.29 (1H, s, H-5), 6.05 (1H, d, *J* 9.4, C=CH), 7.26–7.50 (15H, m, Ar-H); *m*/*z* 466 (M^+, 96%), 393 (100), 293 (11).

Generation of 3,3-diphenylprop-2-eniminium ethoxycarbonylmethyl ylide 3a in the absence of a trapping reagent. *Method* 1.—β-Phenylcinnamaldehyde (0.10 g, 0.48 mmol) and glycine ethyl ester hydrochloride (0.07 g, 0.48 mmol) were dissolved in toluene (6 cm^3), with stirring, and triethylamine (0.05 g, 0.07 cm^3, 0.48 mmol) was added. The mixture was refluxed with the continuous removal of water, using a Dean–Stark trap, for 3 h. The triethylamine hydrochloride was filtered off and the filtrate was refluxed overnight, then allowed to cool to room temperature over 1 h, with stirring. The crude reaction mixture was monitored by TLC. The solvent was evaporated under reduced pressure to give a yellow oil (0.12 g, 86%). The yellow oil, after flash chromatography, eluting with ethyl acetate–light petroleum (40–60 °C) (0:100 to 5:95), gave *ethyl 2-amino-5,5-diphenylpenta-2,4-dienoate* **5a** as a yellow crystalline solid (0.107 g, 75%), mp 91–92 °C (Found: M^+, 293.142. Calc. for $C_{19}H_{19}NO_2$: *M*, 293.142); ν_{max}(liquid film)/cm^{-1} 3448 and 3352 (NH_2), 2899 (CH), 1697 (C=O), 1616 (C=C); δ_H(360 MHz, $CDCl_3$) 1.25 (3H, t, *J* 7.0, CH_3), 4.08 (2H, s, NH_2), 4.21 (2H, q, *J* 7.0, CH_2), 6.25 (1H, d, *J* 12, C=CH), 6.69 (1H, d, *J* 12, C=CH), 7.25–7.30 (7H, m, Ar-H), 7.34–7.41 (3H, m, Ar-H); δ_C(90 MHz, $CDCl_3$) 14.2 (CH_3), 61.3 (CH_2), 108.3 (CH), 121.4 (CH), 127.6 (CH), 127.9 (CH), 128.3 (CH), 130.7 (CH), 133.0 (quat.), 139.5 (quat.), 142.7 (quat.), 143.6 (quat.), 165.3 (quat., C=O); *m*/*z* 293 (M^+, 51%), 220 (23), 149 (100).

Method 2.—The imine **2a** was prepared as described previously, by dissolving β-phenylcinnamaldehyde (0.15 g, 0.72 mmol), glycine ethyl ester hydrochloride (0.1 g, 0.72 mmol) and triethylamine (0.07 g, 0.09 cm^3, 0.72 mmol) in toluene (6 cm^3), with stirring. The mixture was refluxed with the continuous removal of water, using a Dean–Stark trap, for 4 h. The triethylamine hydrochloride was filtered off and acetic acid (10 mol%) was added to the reaction mixture, which was then allowed to stir at room temperature overnight. After the usual work-up, the reaction mixture afforded **5a** as a deep yellow oil (0.17 g, 81%); spectral analysis showed that the product was identical to that obtained previously.

Method 3.—*N*-(Ethoxycarbonylmethyl)-3,3-diphenylprop-2-eminime **2a** (0.25 g, 0.853 mmol) was dissolved in ethanol (100 cm^3). The solution was photolysed using an Osram (330 W) ultra-vitalux lamp, for 2 h. TLC showed a characteristic yellow spot for the product. The solvent was evaporated under reduced pressure to give a pale brown oil (0.18 g, 72%) which was purified by column chromatography on silica, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 5:95) to give a yellow semi-solid (0.153 g, 61%); spectral analysis showed that the product **5a** was identical to that obtained previously.

Ethyl 2-acetamido-5,5-diphenylpenta-2,4-dienoate 6. To a cooled mixture of ethyl 2-amino-5,5-diphenylpenta-2,4-dienoate **5a** (0.2 g, 0.68 mmol) dissolved in pyridine (1 cm^3) at 0 °C, was added acetic anhydride (1.0 g, 1 cm^3, 0.01 mmol). The reaction mixture was allowed to reach room temperature overnight, with stirring. The reaction was then quenched by pouring into ice and the resulting slurry was extracted with DCM (3 × 10 cm^3), and washed with HCl (10 cm^3, 3% v/v) and sat. aq. $NaHCO_3$ (10 cm^3). The organic layer was dried ($MgSO_4$) and the solvent concentrated under reduced pressure to give a white solid, which was then recrystallised from isopropyl alcohol to give **6** as white crystals (0.22 g, 96%), mp 170–171 °C (Found: C, 75.2; H, 6.1; N, 4.2. $C_{21}H_{21}NO_3$ requires C, 75.2; H, 6.3; N, 4.2%) (Found: M^+, 335.152. Calc. for $C_{21}H_{21}NO_3$: *M*, 335.152); ν_{max}(liquid film)/cm^{-1} 3278 (NH), 1716 (C=O), 1654 (C=O), 1601 (C=C); δ_H(270 MHz, $CDCl_3$) 1.22 (3H, t, *J* 7.3, CH_3), 2.17 (3H, s, CH_3), 4.17 (2H, q, *J* 7.3, CH_2), 6.77 (1H, d, *J* 11.9, C=CH), 7.14 (1H, d, *J* 11.9, C=CH), 7.23–7.41 (10H, m, Ar-H); δ_C(68 MHz, $CDCl_3$) 14.6 (CH_3), 24.2 (CH_3), 61.9 (CH_2), 123.3 (CH), 124.5 (CH), 126.6 (CH), 127.9 (CH), 128.3 (CH), 130.7 (CH), 133.0 (quat.), 139.5 (quat.), 142.7 (quat.), 143.6 (quat.), 165.3 (quat., C=O); *m*/*z* 335 (M^+, 18%), 276 (71), 231 (25), 219 (100), 191 (56), 165 (34), 140 (34), 115 (29).

3,3-Diphenylprop-2-eniminium methoxycarbonylmethyl ylide 3b
β-Phenylcinnamaldehyde (0.10 g, 0.48 mmol) glycine methyl ester hydrochloride (0.07 g, 0.57 mmol) and triethylamine (0.10 g, 0.13 cm^3, 0.96 mmol) were dissolved in toluene (6 cm^3). The mixture was refluxed with continuous removal of water, using a Dean–Stark trap, with stirring, for 2 h. The triethylamine hydrochloride was filtered off and the filtrate was placed in an oven-dried flask and refluxed for two days, with stirring, under N_2. The solvent was evaporated under reduced pressure to give a yellow oil (0.13 g, 97%) which was purified by wet column flash chromatography on silica, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 3:97) to give *methyl 2-amino-5,5-diphenylpenta-2,4-dienoate* **5b** as a yellow solid (0.09 g, 67%), mp 134–139 °C (Found: M^+, 279.125. Calc. for $C_{18}H_{17}NO_2$: *M*, 279.126); ν_{max}(liquid film)/cm^{-1} 3428 and 3368 (NH_2), 2923 (CH), 1697 (C=O), 1619 (C=C); δ_H(270 MHz, $CDCl_3$) 3.74 (3H, s, CH_3), 4.10 (2H, br s, NH_2), 6.25 (1H, d, *J* 11.9, C=CH), 6.71 (1H, d, *J* 11.9, C=CH), 7.24–7.38 (10H, m, Ar-H); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 110.1 (CH), 123.7 (CH), 126.8 (CH), 127.3 (CH), 127.9 (CH), 135.1 (quat.), 140.3 (quat.), 142.6 (quat.), 143.1 (quat.), 167.1 (quat., C=O); *m*/*z* 279 (M^+, 89%), 264 (5), 248 (3), 220 (100).

3,3-Bis(4-chlorophenyl)prop-2-eniminium ethoxycarbonylmethyl ylide 3c
N-(Ethoxycarbonylmethyl)-3,3-bis(4-chlorophenyl)prop-2-enimine **2c** (0.359 g, 0.994 mmol) was dissolved in toluene

(8 cm^3). The solution was refluxed for 2 days, with stirring, under N_2. The mixture was allowed to reach room temperature, and the reaction mixture was monitored by TLC, which showed two spots. The solvent was evaporated under reduced pressure to give a yellow–orange oil (0.29 g, 83%). The yellow–orange oil was purified by flash column chromatography, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 5:95), to give two fractions. Fraction one gave 4,4-dichlorobenzophenone as an off-white solid (0.04 g, 17%), mp 142–145 °C; δ_H(270 MHz, $CDCl_3$) 7.44–7.47 (4H, d, *J* 8.1, Ar-H), 7.71–7.74 (4H, d, *J* 8.1, Ar-H). Fraction two gave *ethyl* 2-*amino*-5,5-*bis*(4-*chlorophenyl*)*penta*-2,4-*dienoate* **5c** as a yellow oil (0.18 g, 62%) (Found: M^+, 361.063. Calc. for $C_{19}H_{17}Cl_2NO_2$: *M*, 361.064); ν_{max}(liquid film)/cm^{-1} 3463 and 3382 (NH_2), 2854 (CH), 1704 (C=O), 1617 (C=C); δ_H(270 MHz, $CDCl_3$) 1.21 (3H, t, *J* 7.1, CH_3), 4.10 (2H, q, *J* 7.1, CH_2), 6.09 (1H, d, *J* 12.0, C=CH), 6.59 (1H, d, *J* 12.0, C=CH), 7.08–7.32 (8H, m, Ar-H); δ_C(68 MHz, $CDCl_3$) 14.2 (CH_3), 61.5 (CH_2), 106.9 (CH), 122.1 (CH), 128.4 (CH), 128.5 (CH), 128.7 (CH), 128.9 (CH), 133.5 (quat.), 133.6 (quat.), 133.7 (quat.), 135.4 (quat.), 140.5 (quat.), 141.8 (quat.), 164.9 (quat., C=O); *m*/*z* 365 (M^+, 11%), 363 (M^+, 68), 361 (M^+, 100), 332 (11), 316 (14), 288 (69), 276 (32).

3-Methylbut-2-eniminium ethoxycarbonylmethyl ylide 3e

3-Methylbut-2-enal (0.30 g, 0.34 cm^3, 3.57 mmol) was added to a suspension of glycine ethyl ester hydrochloride (0.37 g, 26.5 mmol) and triethylamine (0.27 g, 0.37 cm^3, 2.65 mmol) in dry THF (10 cm^3), at −20 °C, with stirring, under N_2. The mixture was stirred for 2 h, followed by standing for 1 h, at −20 °C. Na_2CO_3 (2 g) was added and the mixture stirred for a further 2 h at −20 °C. The triethylamine hydrochloride was filtered off and the solvent was evaporated under reduced pressure to give a yellow oil (0.375 g). The crude imine **2e** (0.375 g, 2.21 mmol), DBU (0.336 g, 0.33 cm^3, 2.21 mmol) and LiBr (0.288 g, 3.32 mmol) in acetonitrile (20 cm^3) was stirred at room temperature for two days. The reaction was quenched with sat. aq. NH_4Cl (10 cm^3). The organic layer was separated and the aqueous layer extracted with diethyl ether (3 × 20 cm^3). The combined organic extracts were washed with brine (20 cm^3), dried ($MgSO_4$) and the solvent evaporated under reduced pressure to give an orange–brown oil (0.308 g, 82%). The crude mixture was purified by column chromatography on silica, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 10:90), from which *ethyl* 2-*amino*-5-*methylhexa*-2,4-*dienoate* **5c** was isolated as a pale brown oil (0.0825 g, 22%) (Found: M^+, 169.110. Calc. for $C_9H_{15}NO_2$: *M*, 169.110); ν_{max}(liquid film)/cm^{-1} 3453 and 3382 (NH_2), 1706 (C=O), 1612 (C=C); δ_H(270 MHz, $CDCl_3$) 1.33 (3H, t, *J* 7.2, CH_3), 1.83 (3H, s, CH_3), 1.88 (3H, s, CH_3), 3.73 (2H, br s, NH_2), 4.25 (2H, q, *J* 7.2, CH_2), 5.90 (1H, t, *J* 11.9, C=CH), 6.5 (1H, d, *J* 11.9, C=CH); δ_C(68 MHz, $CDCl_3$) 22.6 (CH_3), 30.6 (CH_3), 31.9 (CH_3), 65.5 (CH_2), 107.8 (CH), 118.7 (CH), 143.2 (quat.), 145.7 (quat.), 167.7 (quat., C=O); *m*/*z* 169 (M^+, 79%), 96 (40), 68 (100).

4-Nitrophenylmethaniminium ethoxycarbonylmethyl ylide 3h

To a solution of *N*-(ethoxycarbonylmethyl)-4-nitrophenylmethanimine **2h** (0.24 g, 1 mmol) in acetonitrile (40 cm^3) was added DBU (0.15 g, 0.15 cm^3, 1 mmol), with stirring, and the reaction mixture was stirred overnight. During this time period, the solution, which was a blue colour, turned green, and then brown. The reaction was monitored by TLC until no further starting material was evident. The reaction mixture was filtered through a pad of silica gel and the solvent evaporated under reduced pressure to give a yellow semi-solid, which was purified by flash chromatography on silica, eluting with ethyl acetate–light petroleum (40–60 °C) (0:100 to 30:70), to give *ethyl* 2-*amino*-3-(4-*nitrophenyl*)*arcylate* **5h** as a yellow crystalline solid; (0.14 g, 60%), mp 104 °C (Found: MH^+, 237.087. Calc. for $C_{11}H_{13}N_2O_4$: *MH*$^+$, 237.0875); ν_{max}(liquid film)/cm^{-1} 3374 (NH_2), 1708 (C=O), 1585 (C=C); δ_H(270 MHz, $CDCl_3$) 1.39 (3H, t, *J* 7.3, CH_3), 4.36 (2H, q, *J* 7.3, CH_2), 4.56 (2H, br s, NH_2), 6.43 (1H, s, C=CH), 7.56 (2H, d, *J* 8.6, Ar-2′, 6′H), 8.22 (2H, d, *J* 8.6, Ar-3′, 5′H); δ_C(68 MHz, $CDCl_3$) 14.2 (CH_3), 62.2 (CH_2), 105.2 (CH), 124.2 (CH), 128.4 (CH), 135.1 (quat.), 143.5 (quat.), 145.5 (quat.), 165.0 (quat., C=O); *m*/*z* 237 (MH^+, 100%), 220 (28), 208 (15), 191 (10), 163 (50), 132 (12), 89 (11).

3-Nitrophenylmethaniminium ethoxycarbonylmethyl ylide 3i

(**a**) This was prepared, as described above, from *N*-(ethoxycarbonylmethyl)-3-nitrophenylmethanimine (0.24 g, 1 mmol) in acetonitrile (40 cm^3) and DBU (0.15 g, 0.15 cm^3, 1 mmol), to give *ethyl* 2-*amino*-3-(3-*nitrophenyl*)*arcylate* **5i** as a yellow crystalline solid, (0.13 g, 55%), mp 97–98 °C (Found: M^+, 236.079. Calc. for $C_{11}H_{12}N_2O_4$: *M*, 236.079); ν_{max}(liquid film)/cm^{-1} 3355 (NH_2), 1708 (C=O), 1604 (C=C); δ_H(270 MHz, $CDCl_3$) 1.39 (3H, t, *J* 6.6, CH_3), 4.34 (2H, q, *J* 6.6, CH_2), 4.43 (2H, br s, NH_2), 6.44 (1H, s, C=CH), 7.53 (1H, t, *J* 7.3, Ar-5′H), 7.74 (1H, d, *J* 7.3, Ar-6′H), 8.03 (1H, dt, *J* 2.0, 7.3, Ar-4′H), 8.28 (1H, t, *J* 2.0, Ar-2′H); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 62.0 (CH_2), 105.4 (CH), 121.0 (CH), 122.5 (CH), 129.6 (CH), 133.8 (CH), 134.3 (quat.), 138.2 (quat.), 148.6 (quat.), 165.1 (quat., C=O); *m*/*z* 236 (M^+, 100%), 208 (15), 162 (99), 132 (53), 116 (32), 89 (68), 63 (28).

(**b**) *N*-(Ethoxycarbonylmethyl)-3-nitrophenylmethanimine (0.45 g, 1.9 mmol), *N*-phenylmaleimide (0.325 g, 1.9 mmol), and lithium bromide (0.198 g, 2.28 mmol) were dissolved in acetonitrile (40 cm^3) and DBU (0.29 g, 0.28 cm^3, 1.9 mmol) was added to the stirred mixture. After 2 h the reaction mixture was diluted with saturated aqueous ammonium chloride (25 cm^3) and extracted with diethyl ether (2 × 25 cm^3). The organic layer was dried over magnesium sulfate, evaporated, and the residue was recrystallised from light petroleum–ethyl acetate to give the product **16** as a yellow powder (0.62 g, 80%), mp 137–138 °C (Found: M^+, 409.127. Calc. for $C_{21}H_{19}N_3O_6$: *M*$^+$, 409.127); ν_{max}(liquid film)/cm^{-1} 3336 (NH), 1730 and 1712 (C=O); δ_H(270 MHz, $CDCl_3$) 1.36 (3H, t, *J* 7.3, CH_3), 3.63 (1H, t, *J* 7.9, H-2a), 3.76 (1H, t, *J* 7.9, H-5a), 4.16 (1H, d, *J* 7.9, H-3), 4.33 (2H, m, OCH_2), 4.67 (1H, d, *J* 7.9, H-5), 7.13 (2H, d, *J* 7.3, Ar-H), 7.29–7.43 (3H, m, Ar-H), 7.51 (1H, t, *J* 7.9, Ar-5′H), 7.80 (1H, d, *J* 7.9, Ar-4′H), 8.14 (1H, d, *J* 7.9, Ar-6′H), 8.33 (1H, s, Ar-2′H); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 47.6 (CH_2), 49.1 (CH), 60.3 (CH), 61.6 (CH), 63.1 (CH), 122.3 (CH), 123.4 (CH), 126.2 (CH), 128.7 (CH), 129.0 (CH), 129.2 (CH), 131.4 (quat.), 133.3 (CH), 139.3 (quat.), 148.3 (quat.), 169.2 (quat., C=O), 173.5 (quat., C=O), 174.6 (quat., C=O); *m*/*z* 409 (M^+, 100%), 336 (100), 236 (15), 189 (88), 162 (43), 143 (37), 115 (24).

3,3-Diphenylprop-2-eniminium-1-ethoxycarbonyl-2-phenylethyl ylide 3n

Trapping of 3,3-diphenylprop-2-eniminium 1-ethoxycarbonyl-2-phenylethyl ylide 3n with *N*-phenylmaleimide. β-Phenylcinnamaldehyde (0.20 g, 0.96 mmol) and phenylalanine ethyl ester hydrochloride (0.22 g, 0.96 mmol) were dissolved in toluene (6 cm^3) and triethylamine (0.10 g, 0.14 cm^3, 0.96 mmol). The mixture was refluxed with the continuous removal of water, using a Dean–Stark trap, for 3 h. The triethylamine hydrochloride was filtered off and *N*-phenylmaleimide (0.12 g, 0.72 mmol) was added. The mixture was then refluxed for 4 h and the reaction monitored by TLC. On cooling, *ethyl* 2-*benzyl*-6,8-*dioxo*-7-*phenyl*-4-(2′,2′-*diphenylethenyl*)-3,7-*diazabicyclo*[3.3.0]-*octane*-2-*carboxylate* **8** precipitated as a white solid (0.16 g, 57%), mp 182–184 °C (Found: M^+, 556.236. Calc. for $C_{36}H_{32}N_2O_4$: *M*, 556.236); ν_{max}(liquid film)/cm^{-1} 1731 (C=O), 1712 (C=O); δ_H(360 MHz, $CDCl_3$) 1.26 (3H, t, *J* 7.0, CH_3), 2.75 (1H, d, *J* 13.6, CH), 3.35 (1H, d, *J* 13.6, CH), 3.39 (2H, m, CH), 4.25 (3H, m, CH + CH_2), 5.93 (1H, d, *J* 9.6, C=CH), 6.91 (2H, m, Ar-H), 7.20–7.45 (18H, m, Ar-H); δ_C(68 MHz, $CDCl_3$) 14.1 (CH_3), 41.1 (CH_2), 49.9 (CH), 55.6 (CH), 55.7 (CH), 57.5 (CH), 61.9 (CH_2), 124.4 (CH), 126.5 (CH), 127.2 (quat.), 127.7 (CH), 127.8 (CH), 128.2 (CH), 128.4 (CH), 128.7 (quat.), 129.2

(quat.), 129.6 (CH), 129.9 (CH), 135.4 (quat.), 139.6 (quat.), 141.5 (quat.), 146.4 (quat.), 170.9 (quat., C=O), 174.1 (quat., C=O), 174.7 (quat., C=O); *m/z* 556 (M^+, 6%), 483 (22), 465 (100), 383 (22), 310 (6), 192 (41).

5-Nitro-2-furylmethaniminium ethoxycarbonylmethyl ylide 13

To a solution of glycine ethyl ester hydrochloride (5.53 g, 39.2 mmol), 5-nitro-2-furaldehyde **9** (5.53 g, 39.2 mmol) and triethylamine (5.46 cm^3, 39.2 mmol) in dichloromethane (250 cm^3) was added $MgSO_4$ (27 g) and *N*-phenylmaleimide (6.79 g, 39.2 mmol). After 30 min the reaction became dark brown in colour. After stirring at room temperature for 24 h, silica gel (25 g) was added, and the solvent removed under reduced pressure. The residue was applied to a flash silica column and elution with light petroleum–ethyl acetate (80:20) gave the dehydroamino acid ester **12**[14] as an orange oil (0.11 g, 1%). Further elution with light petroleum–ethyl acetate (50:50) gave an orange oil for the cycloadduct **14**, as a 50:50 mixture of two isomers (3.84 g, 25%) (Found: M^+, 399.107. Calc. for $C_{19}H_{17}N_3O_7$: *M*, 399.107); ν_{max}(liquid film)/cm^{-1} 3328 (NH), 1716 (C=O), 1355 and 1357 (NO_2); δ_H(270 MHz, $CDCl_3$) 1.35 (6H, t, *J* 7), 3.35 (1H, d, *J* 5), 3.72 (1H, t, *J* 8.6), 3.86 (3H, m), 4.05 (1H, d, *J* 12), 4.30 (4H, 2 × q, *J* 7), 4.90 (2H, m), 5.58 (1H, d, *J* 11), 6.60 (1H, d, *J* 4), 6.66 (1H, d, *J* 3), 7.23–7.47 (13H, m, Ar-H); *m/z* 399 (M^+, 18%), 382 (35), 326 (75), 274 (50), 119 (51), 91 (100), 77 (77).

Catalytic reactions

Methyl (*Z*)-2-amino-3-phenylacrylate 5j

N-(Methoxycarbonylmethyl)-3,3-diphenylprop-2-enimine **2b** (0.0158 g, 5.646×10^{-5} mol), *N*-(methoxycarbonylmethyl)-benzaldimine **2j** (0.1999 g, 1.129 mmol) and triethylamine (2 drops) were dissolved in toluene (10 cm^3) and the mixture was refluxed for 5 days. The solvent was evaporated under reduced pressure to give a murky yellow oil (0.1548 g). This oil, after flash chromatography, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 2:98), gave two products. Fraction one gave imine **17j** as a yellow oil[25] (0.043 g, 27%), δ_H(270 MHz, $CDCl_3$) 3.70 (3H, s, OCH_3), 7.18 (1H, s, C=CH), 7.27–7.30 (3H, m, Ar-H), 7.42–7.44 (3H, m, Ar-H), 7.62–7.65 (2H, m, Ar-H), 7.83–7.87 (2H, m, Ar-H), 8.57 (1H, s, CH=N); *m/z* 265 (M^+, 78%), 250 (22), 236 (11), 220 (33), 204 (100), 192 (22), 161 (34). Fraction two gave **5j** as a pale yellow semi-solid[26] (0.053 g, 34%) (Found: M^+, 177.078. Calc. for $C_{10}H_{11}NO_2$: *M*, 177.079); ν_{max}(liquid film)/cm^{-1} 3483 and 3370 (NH_2), 2924 (CH), 2854 (CH), 1708 (C=O), 1628 (C=C), 1596 (C=C); δ_H(270 MHz, $CDCl_3$) 3.79 (3H, s, OCH_3), 4.15 (2H, br s, NH_2), 6.41 (1H, s, C=CH), 7.15–7.83 (5H, m, Ar-H); δ_C(68 MHz, $CDCl_3$) 29.7 (CH_3), 109.3 (CH), 126.8 (quat.), 128.3 (CH), 128.7 (CH), 129.0 (CH), 131.5 (quat.), 164.4 (quat., C=O); *m/z* 177 (M^+, 100%), 162 (4), 118 (89), 106 (81), 90 (80), 77 (72).

Ethyl 2-amino-3-(4-methoxyphenyl)acrylate 5k

This was prepared, as described above, from *N*-(ethoxycarbonylmethyl)-3,3-diphenylprop-2-enimine **2a** (0.029 g, 0.1 mmol), *N*-(ethoxycarbonylmethyl)-4-methoxyphenylmethanimine **2k** (0.44 g, 2 mmol) and triethylamine (0.20 g, 0.28 cm^3, 2 mmol) in toluene (40 cm^3), to give *ethyl* 2-*amino*-3-(4-*methoxyphenyl*)*acrylate* **5k** as a colourless oil, after refluxing for 13 days (0.066 g, 15%) (Found: M^+, 221.105. Calc. for $C_{12}H_{15}NO_3$: *M*, 221.105); ν_{max}(liquid film)/cm^{-1} 3370 (NH_2), 1700 (C=O), 1600 (C=C); δ_H(270 MHz, $CDCl_3$) 1.22 (3H, t, *J* 7.3, CH_3), 3.81 (3H, s, CH_3), 4.29 (2H, q, *J* 7.3, CH_2), 6.48 (1H, s, C=CH), 6.88 (2H, d, *J* 9.2, Ar-3′, 5′H), 7.41 (2H, d, *J* 9.2, Ar-2′, 6′H); δ_C(68 MHz, $CDCl_3$) 14.3 (CH_3), 55.2 (CH_3), 61.5 (CH_2), 110.2 (CH), 129.7 (2 × CH), 132.0 (2 × CH), 136.7 (quat.), 139.2 (quat.), 162.5 (quat.), 165.1 (quat., C=O); *m/z* 221 (M^+, 100%), 205 (32), 192 (17), 160 (89), 148 (53).

Ethyl 2-(4-fluorobenzylideneimino)-3-(4-fluorophenyl)acrylate 17l

N-(Ethoxycarbonylmethyl)-3,3-diphenylprop-2-enimine **2a** (0.029 g, 0.1 mmol), *N*-(ethoxycarbonylmethyl)-4-fluorophenylmethanimine **2l** (0.42 g, 2 mmol) and triethylamine (0.20 g, 0.28 cm^3, 2 mmol) were dissolved in toluene (40 cm^3) and the mixture was refluxed for 9 days. The solvent was evaporated under reduced pressure to give a yellow oil. The reaction afforded the mixture of products by TLC. This yellow oil was purified by column chromatography on silica, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 20:80) to give *ethyl* 2-(4-*fluorobenzylideneimino*)-3-(4-*fluorophenyl*)*acrylate* **17l** as a pale yellow solid (0.19 g, 18%), mp 73 °C (Found: M^+, 315.107. Calc. for $C_{18}H_{15}F_2NO_2$: *M*, 315.107); ν_{max}(liquid film)/cm^{-1} 1712 (C=O), 1650 (C=N), 1600 (C=C); δ_H(270 MHz, $CDCl_3$) 1.38 (3H, t, *J* 7.2, CH_3), 4.33 (2H, q, *J* 7.2, CH_2), 7.04 (2H, tt, *J* 8.6, 2.0, Ar-2′, 6′H), 7.18 (2H, tt, *J* 8.6, 2.0, Ar-2′, 6′H), 7.22 (1H, s, C=CH), 7.70 (2H, m, Ar-3′, 5′H), 7.90 (2H, m, Ar-3′, 5′H), 8.59 (1H, s, CH=N); δ_C(68 MHz, $CDCl_3$) 14.8 (CH_3), 61.9 (CH_2), 115.9 (*J* 22, 2 × CH), 116.5 (*J* 22, 2 × CH), 126.8 (CH), 127.5 (quat.), 131.4 (*J* 8.8, 2 × CH), 132.2 (quat.), 133.1 (quat.), 133.9 (*J* 8.8, 2 × CH), 137.5 (quat.), 145.3 (quat.), 163.5 (CH), 165.1 (quat., C=O); *m/z* 315 (M^+, 25%), 242 (35), 220 (27), 174 (30), 146 (38), 123 (100), 107 (60), 95 (38).

Ethyl 2-amino-3-(4-chlorophenyl)acrylate 5m

N-(Ethoxycarbonylmethyl)-3,3-diphenylprop-2-enimine **2a** (0.029 g, 0.1 mmol), *N*-(ethoxycarbonylmethyl)-3-chlorobenzaldimine **2m** (0.45 g, 2 mmol) and triethylamine (0.20 g, 0.28 cm^3, 2 mmol) in toluene (40 cm^3) were reacted, using the above method, to give *ethyl* 2-*amino*-3-(4-*chlorophenyl*)*acrylate* **5m** as a colourless oil, after refluxing for 9 days (0.16 g, 35%) (Found: M^+, 225.055. Calc. for $C_{11}H_{12}ClNO_2$: *M*, 225.056); ν_{max}(liquid film)/cm^{-1} 3367 (NH_2), 1708 (C=O), 1592 (C=C); δ_H(270 MHz, $CDCl_3$) 1.37 (3H, t, *J* 7.1, CH_3), 4.20 (2H, br s, NH_2), 4.33 (2H, q, *J* 7.1, CH_2), 6.41 (1H, s, C=CH), 7.32 (2H, d, *J* 9.0, Ar-H), 7.83 (2H, d, *J* 9.0, Ar-H); δ_C(68 MHz, $CDCl_3$) 14.2 (CH_3), 62.2 (CH_2), 105.2 (CH), 124.2 (CH), 128.4 (CH), 135.1 (quat.), 143.5 (quat.), 145.5 (quat.), 165.0 (quat., C=O); *m/z* 227 (M^+, 6%), 225 (M^+, 18%), 197 (7), 149 (100), 139 (20), 125 (29), 117 (21), 89 (47), 71 (16), 57 (35).

Mechanistic studies

Attempted crossover reaction of dehydroamino acid esters 5b and 5c

Methyl 2-amino-5,5-diphenylpenta-2,4-dienoate **5b** (0.0425 g, 0.15 mmol) and ethyl 2-amino-5,5-bis(4-chlorophenyl)penta-2,4-dienoate **5c** (0.0515 g, 0.14 mmol) were dissolved in toluene (8 cm^3). The mixture was refluxed overnight. After cooling the solvent was evaporated under reduced pressure to give a yellow oil (0.093 g), the ^1H NMR and mass spectra of which showed only the recovered didehydroamino acid esters **5b** and **5c**.

Crossover reaction of imines 2b and 2c

N-(Ethoxycarbonylmethyl)-3,3-bis(4-chlorophenyl)prop-2-enimine **2c** (0.0170 g, 4.71×10^{-5} mol) and *N*-(methoxycarbonylmethyl)-3,3-diphenylprop-2-enimine **2b** (0.0168 g, 4.71×10^{-5} mol) were dissolved in toluene (10 cm^3). The mixture was allowed to reflux for three days and continuously monitored by TLC, which showed a mixture of products. The solvent was removed under reduced pressure to give a deep yellow oil (0.0318 g), which was purified by column chromatography on silica, eluting with ethyl acetate–light petroleum (60–80 °C) (0:100 to 4:96), to give three fractions. Fraction one gave a yellow oil (3.49 mg), which NMR analysis showed was recovered aldehydes. Fraction two gave a mixture of ethyl esters **5a** and **5c** as a pale yellow oil (0.012 g); δ_H(270 MHz, $CDCl_3$) 1.21 (6H, t, *J* 7.1, CH_3), 4.17 (4H, m, CH_2), 6.09 (1H, d, *J* 11.9,

C=CH), 6.19 (1H, d, *J* 12.0, C=CH), 6.61 (2H, m, C=CH), 7.05–7.32 (18H, m, Ar-H); *m/z* 365 (M^+ **5c**, 1%), 363 (M^+, 7), 361 (M^+, 13), 332 (5), 316 (13), 300 (8), 293 (M^+ **5a**, 15%), 288 (100), 264 (8), 220 (51). Fraction three gave a mixture of the methyl esters **5b** and **5d** as a yellow oil (0.016 g); δ_H(270 MHz, $CDCl_3$) 3.67 (3H, s, CH_3), 3.69 (3H, s, CH_3), 4.1 (4H, br s, NH_2), 6.07 (1H, d, *J* 11.9, C=CH), 6.17 (1H, d, *J* 12.0, C=CH), 6.60 (1H, d, *J* 11.9, C=CH), 6.63 (1H, d, *J* 11.9, C=CH), (18H, m, Ar-H); *m/z* 351 (M^+ **5d**, 11%), 349 (M^+, 69), 347 (M^+ **5b**, 97), 332 (19), 316 (9), 300 (5), 288 (100), 279 (M^+, 30%), 264 (8), 179 (19).

Ethyl 1-ethoxycarbonyl-2,5-bis(3-nitrophenyl)imidazolidine-4-carboxylate 7i

N-(Ethoxycarbonylmethyl)-3-nitrophenylmethanimine **2i** (0.24 g, 1.02 mmol) was dissolved in anhydrous acetonitrile (20 cm^3) and $MgClO_4$ (0.33 g, 1.5 mmol) was added, with stirring. The reaction mixture was stirred for 24 h, and the reaction quenched with sat. NH_4Cl solution (20 cm^3). The organic layer was separated and the aqueous phase extracted with diethyl ether (3 × 20 cm^3). The combined organic extracts were dried ($MgSO_4$) and the solvent evaporated under reduced pressure to give a white semi-solid (0.21 g, 88%), which was purified by column chromatography on silica, eluting with ethyl acetate–light petroleum (40–60 °C) (0:100 to 30:70), to give two fractions. Fraction one gave the *syn-exo* isomer **7i** as a colourless oil (78 mg, 33%) (Found: M^+, 472.157. Calc. for $C_{22}H_{24}N_4O_8$: *M*, 472.159); ν_{max}(liquid film)/cm^{-1} 3320 (NH), 2923 (CH), 2854 (CH), 1735 (C=O), 1531 (C=C); δ_H(270 MHz, $CDCl_3$) 1.21 (3H, t, *J* 6.6, CH_3), 1.29 (3H, t, *J* 6.6, CH_3), 3.23 (1H, d, *J* 17.0, CH_a), 3.32 (1H, d, *J* 17.0, CH_b), 3.87 (1H, d, *J* 6.6, H-4), 4.12 (2H, q, *J* 6.6, CH_2), 4.21–4.37 (2H, 2 × dq, CH_2), 4.62 (1H, d, *J* 6.6, H-5), 5.35 (1H, s, H-2), 7.61 (1H, t, *J* 7.9, Ar-5′H), 7.62 (1H, t, *J* 7.9, Ar-5′H), 7.91 (1H, d, *J* 7.9, Ar-6′H), 7.97 (1H, d, *J* 7.9, Ar-6′H), 8.22 (2H, m, 2 × Ar-4′H), 8.36 (1H, d, *J* 2, Ar-2′H), 8.47 (1H, d, *J* 2, Ar-2′H); δ_C(68 MHz, $CDCl_3$) 14.0 (CH_3), 14.1 (CH_3), 48.2 (CH_2), 60.8 (CH_2), 61.7 (CH_2), 66.8 (CH), 68.4 (CH), 78.7 (CH), 122.8 (CH), 123.0 (CH), 123.2 (CH), 123.8 (CH), 133.5 (CH), 134.2 (CH), 142.6 (quat.), 143.0 (quat.), 148.5 (2 × quat.), 169.7 (quat., C=O), 171.8 (quat., C=O); *m/z* 472 (M^+, 5%), 443 (32), 399 (61), 385 (82), 237 (100), 163 (95), 117 (76). Fraction two gave the *syn-endo* isomer **7i′** as a white solid (25 mg, 10%), mp 123–125 °C (Found: M^+, 472.158. Calc. for $C_{22}H_{24}N_4O_8$: *M*, 472.159); ν_{max}(liquid film)/cm^{-1} 1724 (C=O), 1527 (C=C); δ_H(270 MHz, $CDCl_3$) 0.87 (3H, t, *J* 7.3, CH_3), 1.20 (3H, t, *J* 7.2, CH_3), 3.25 (1H, d, *J* 17, CH_a), 3.39 (1H, d, *J* 17, CH_b), 3.55 (1H, dq, $CH_{a'}$), 3.80 (1H, dq, $CH_{a'}$), 4.08 (2H, q, *J* 7.3, CH_2), 4.50 (1H, d, *J* 9.0, H-4), 4.87 (1H, d, *J* 9.0, H-5), 5.27 (1H, s, H-2), 7.57 (1H, t, *J* 7.9, Ar-5′H), 7.69 (1H, t, *J* 7.9, Ar-5′H), 7.85 (1H, d, *J* 7.9, Ar-6′H), 8.08 (1H, d, *J* 7.9, Ar-6′H), 8.18 (1H, d, *J* 7.9, Ar-4′H), 8.30 (2H, m, Ar-4′H and Ar-2′H), 8.52 (1H, s, Ar-2′H); δ_C(68 MHz, $CDCl_3$) 14.0 (CH_3), 14.5 (CH_3), 48.6 (CH_2), 61.2 (CH_2), 61.8 (CH_2), 65.1 (CH), 67.4 (CH), 79.6 (CH), 123.6 (2 × CH), 123.7 (CH), 124.7 (CH), 129.8 (CH), 130.6 (CH), 134.4 (CH), 134.5 (CH), 141.0 (quat.), 141.8 (quat.), 148.6 (quat.), 149.1 (quat.), 170.2 (quat., C=O), 170.6 (quat., C=O); *m/z* 472 (M^+, 21%), 443 (100).

Reactions of imidazolidine 7i

With DBU. Ethyl 1-ethoxycarbonyl-2,5-bis(3-nitrophenyl)-imidazolidine-4-carboxylate **7i**,**i′** (0.47 g, 1 mmol) and DBU (0.15 g, 0.14 cm^3, 1 mmol) were dissolved in acetonitrile (10 cm^3), with stirring, at room temperature. The mixture was stirred overnight and the solvent evaporated under reduced pressure, to give a yellow oil (0.19 g, 80%), which was purified by wet flash chromatography on silica, eluting with ethyl acetate–light petroleum (40–60 °C) (0:100 to 30:70), to give **5i** as a yellow semi-solid (0.11 g, 51%); spectral analysis showed that the product was identical to that obtained previously.

With DDQ. A solution of ethyl 1-ethoxycarbonyl-2,5-bis(3-nitrophenyl)imidazolidine-4-carboxylate (*syn-exo*) **7i** (0.22 g, 0.46 mmol) and DDQ (0.10 g, 0.46 mmol) was refluxed in toluene (cm^3) for 12 h. The solvent was evaporated and the residue was purified using column chromatography on silica, eluting with ethyl acetate–light petroleum (40–60 °C), to give **15** as a pale yellow oil (0.154 g, 71%) (Found: MH^+, 471.152. Calc. for $C_{22}H_{23}N_4O_8$: *M*, 471.152); ν_{max}(liquid film)/cm^{-1} 1739 (C=O), 1608 (C=C), 1531 and 1446 (NO_2); δ_H($CDCl_3$) 1.18 (3H, t, *J* 7.0, CH_3), 1.37 (3H, t, *J* 7.0, CH_3), 3.70 (1H, d, *J* 17.8, CH_aN), 3.96 (1H, d, *J* 17.8, CH_bN), 4.09 (2H, q, *J* 7.3, OCH_2), 4.30 (2H, m, OCH_2), 4.64 (1H, d, *J* 9.2, H-4), 5.24 (1H, d, *J* 9.2, H-5), 7.62–7.74 (2H, m, Ar-5′H), 7.85 (1H, d, *J* 7.9, Ar-6′H), 8.07 (1H, d, *J* 7.9, Ar-6′H), 8.24 (1H, dd, *J* 7.9, 1.3, Ar-4′H), 8.31–8.38 (2H, m, Ar-2′H and 4′H), 8.53 (1H, s, Ar-2′H); δ_C(68 MHz, $CDCl_3$) 13.8 (CH_3), 14.0 (CH_3), 49.4 (CH_2), 61.2 (CH_2), 61.3 (CH_2), 64.5 (CH), 67.2 (CH), 123.6 (CH), 124.0 (CH), 125.1 (quat.), 125.5 (CH), 127.8 (CH), 127.9 (quat.), 128.2 (CH), 128.5 (CH), 128.8 (CH), 129.0 (CH), 129.2 (quat.), 132.4 (quat.), 134.0 (quat.), 170.5 (quat. C=O), 173.0 (quat., C=O); *m/z* 471 (MH^+, 97), 441 (13), 420 (14), 397 (100), 367 (12), 323 (9), 237 (11), 41 (62).

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References

1 (*a*) T. J. Nitz, E. M. Holt, B. Rubin and C. H. Stammer, *J. Org. Chem.*, 1981, **46**, 2667; (*b*) M. D. Grim, V. Chauhan, Y. Shimohigashi, A. J. Kolar and C. H. Stammer, *J. Org. Chem.*, 1981, **46**, 2671; (*c*) T. V. Rajan Babu, T. A. Ayers, G. A. Halliday, K. K. You and J. C. Calabrese, *J. Org. Chem.*, 1997, **62**, 6012.

2 For a review see, W. S. Knowles, *Acc. Chem. Res.*, 1983, **16**, 106. Recent example: A. S. C. Chan, W. H. Hu, C.-C. Pai, C.-P. Lau, Y. Z. Jiang, A. Q. Mi, M. Yan, J. Sun, R. L. Lou and J. G. Deng, *J. Am. Chem. Soc.*, 1997, **119**, 9570.

3 (*a*) C. H. Stammer, *Chemistry and Biochemistry of Amino Acids, Peptides and Proteins*, John Wright and Sons Ltd., London, 1982, vol. 6, p. 33; (*b*) H. G. Floss and J. C. Vederas, in *New Comprehensive Biochemistry*, *Vol. 3*: *Stereochemistry*, ed. C. Tamm, Elsevier Science, Amsterdam, 1982, p. 161.

4 T. Takita, T. Tamura and H. Taniyama, *J. Biochem.*, 1977, **81**, 1759.

5 See, for example, (*a*) M. J. Burk, J. G. Allen, W. F. Kiesman and K. M. Stoffan, *Tetrahedron Lett.*, 1997, **38**, 1309; (*b*) U. Schmidt, A. Lieberknecht and J. Wild, *Synthesis*, 1988, 159 and references therein; (*c*) R. Grigg and J. Kemp, *J. Chem. Soc.*, *Chem. Commun.*, 1977, 125.

6 P. W. Groundwater, T. Sharif, A. Arany, D. E. Hibbs, M. B. Hursthouse and M. Nyerges, *Tetrahedron Lett.*, 1998, **39**, 1433.

7 (*a*) P. W. Groundwater, C. Struthers-Semple and J. T. Sharp, *J. Chem. Soc.*, *Chem. Commun.*, 1987, 1367; (*b*) P. W. Groundwater and J. T. Sharp, *Tetrahedron*, 1992, **48**, 7951; (*c*) P. W. Groundwater, A. J. Morton and R. Salter, *J. Chem. Soc.*, *Chem. Commun.*, 1993, 1789.

8 R. Grigg and V. Sridharan, in *Advances in Cycloaddition*, ed. D. P. Curran, JAI Press, 1993, vol. 3, p. 161.

9 W. Nagata, T. Wakabayashi and Y. Hayase, *Org. Synth.*, 1988, **Coll. Vol. VI**, 448.

10 R. Grigg, *Chem. Soc. Rev.*, 1987, **16**, 89.

11 R. Grigg, H. Q. N. Gunaratne and J. Kemp, *J. Chem. Soc.*, *Perkin Trans. 1*, 1984, 41.

12 R. Grigg and H. Q. N. Gunaratne, *J. Chem. Soc.*, *Chem. Commun.*, 1982, 384.

13 K. Amornraksa, D. Barr, G. Donegan, R. Grigg, P. Ratananukul and V. Sridharan, *Tetrahedron*, 1989, **45**, 4649.

14 H. Cerecetto, R. Di Maio, M. Gonzalez and G. Seoane, *Heterocycles*, 1997, **45**, 2023.

15 M. Nyerges, M. Rudas, G. Toth, B. Herenyi, I. Bitter and L. Toke, *Tetrahedron*, 1995, **51**, 13 321.

16 O. Tsuge, S. Kanemasa, T. Yamada and K. Matsuda, *J. Org. Chem.*, 1987, **52**, 2523.

17 D. D. Perrin and W. L. F. Armarego, *Purification of Organic Compounds*, 3rd edn., Pergamon Press, Oxford, 1988.
18 O. Tsuge, S. Kanemasa, M. Ohe, K. Yorozu, S. Takenaka and K. Ueno, *Chem. Lett.*, 1986, 1271.
19 M. A. El Maghraby and K. M. Hassan, *Indian J. Chem.*, 1973, **11**, 1205.
20 J.-P. Genet, S. Juge, S. Achi, S. Mallart, J. Montes and G. Levif, *Tetrahedron*, 1988, **44**, 5263.
21 J. A. Darr, S. R. Drake and M. B. Hursthouse, *Inorg. Chem.*, 1993, **32**, 5704.
22 G. M. Sheldrick, *Acta. Crystallogr.*, *Sect. A*, 1990, **46**, 467.
23 G. M. Sheldrick, SHELXL-93: *Program for Crystal Structure Refinement*, University of Göttingen, Germany.
24 D. G. Farnum, M. Ghandi, S. Raghu and T. Reitz, *J. Org. Chem.*, 1982, **47**, 2598.
25 O. Mamoun, H. Benhaoua, R. Danion-Bougot and D. Danion, *Synth. Commun.*, 1995, **25**, 1295.
26 T. Moriya, K. Matsumoto and M. Miyoshi, *Synthesis*, 1981, 915.

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