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Aza-Baylis–Hillman reactions of diisopropyl azodicarboxylate or diethyl azodicarboxylate with acrylates and acrylonitrile

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Abstract—It has been found that in the Baylis–Hillman reactions of DIAD or DEAD with acrylates or acrylonitrile, the Lewis base and solvent can significantly affect the reaction rate. Using DABCO as Lewis base in DMF or THF, the corresponding aza-Baylis–Hillman adducts **2** or **3** can be obtained in moderate to good yields.

1. Introduction

Since Baylis and Hillman first reported the reactions of acetaldehyde with ethyl acrylate and acrylonitrile in the presence of catalytic amounts of a strong Lewis base such as 1,4-diazabicyclo[2.2.2]octane (DABCO) in 1972,[1] the Baylis–Hillman reaction has made great progress,[2] advancing to a catalytic asymmetric version.[3] However, in this very simple and useful reaction, only aldehydes (RCHO),[1–3] *N*-arylidene-4-methylbenzenesulfonamides (ArCH=NTs),[4] and *N*-arylidenediphenylphosphinamides [ArCH=NP(O)Ph_2][5] are in general used as the substrates for the reaction with α,β-unsaturated ketones, nitriles or esters. In 1998, Kamimura and co-workers reported a facile preparation of α-hydrazino-α,β-unsaturated ketones via aza-Baylis–Hillman reaction of diethyl azodicarboxylate (DEAD) or di-*tert*-butyl azodicarboxylate with α,β-unsaturated ketones catalyzed by DABCO.[6] In that paper, they mentioned that no reaction occurred in the aza-Baylis–Hillman reaction of DEAD with methyl acrylate under the same conditions.[6] During our comprehensive investigations on the aza-Baylis–Hillman reaction,[4,5] we found that the aza-Baylis–Hillman reaction of DEAD with methyl acrylate indeed produced a polymeric compound, but the corresponding aza-Baylis–Hillman adducts can be garnered in moderate to high yields if either DIAD is used as a substrate or other acrylates are used as the Michael acceptors. Herein, we report the aza-Baylis–Hillman reaction of diisopropyl azodicarboxylate (DIAD) and DEAD with various acrylates and acrylonitrile in the presence of an array of Lewis bases.[5]

2. Results and discussion

At first, we systematically examined the promoters and solvents for the aza-Baylis–Hillman reaction of DIAD with methyl vinyl ketone (MVK) (Table 1) to search for the optimal conditions.[7] We found that the Lewis bases and solvents played very important roles for this reaction. Phosphane Lewis bases such as triphenylphosphine (PPh_3) showed no catalytic activity for this reaction (Table 1, entry 5). Nitrogen Lewis bases such as DABCO, 4-*N*,*N*-dimethylpyridine (DMAP), triethylamine (Et_3N) and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) could serve as effective promoters to give the corresponding adduct **1** in moderate to high yields (Table 1, entries 1–4 and 6–9). DMF or THF is the solvent of choice. Lewis base DABCO gave the best result in DMF (Table 1, entry 1). In all these cases, the normal aza-Baylis–Hillman adduct **1** was formed exclusively.

The reaction was further investigated using DABCO as a Lewis base and phenyl acrylate as a Michael acceptor[8] and it was found that the corresponding aza-Baylis–Hillman adduct **2a** was obtained in good yield. Its structure was determined by spectroscopic data and microanalysis.

We then examined the solvent effect in this type of aza-Baylis–Hillman reaction at room temperature. The results are summarized in Table 2. In THF or DMF, adduct **2a** was obtained in 71 and 81% yield (Table 2, entries 1 and 2), respectively. On the other hand, MeCN or dichloromethane gave lower yields of 58 and 62% (Table 2, entries 3 and 4),

Keywords: Diisopropyl azodicarboxylate; Diethyl azodicarboxylate; Lewis base DABCO; Aza-Baylis–Hillman reaction.
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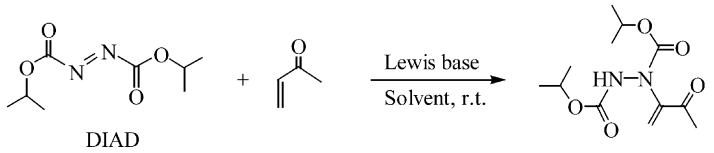
Table 1. The effects of Lewis base and solvent in the aza-Baylis–Hillman reaction of DIAD with MVK

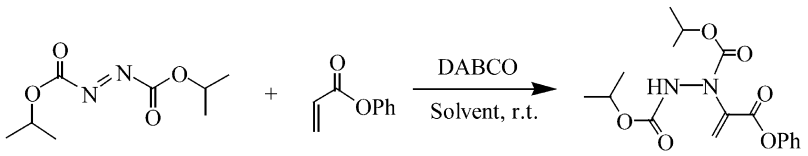


DIAD **1**

Entry	Lewis base	Solvent	Time (h)	Yield (%)[a] (**1**)
1	DABCO	THF	12	94
2	DABCO	DMF	12	63
3	DMAP	THF	12	68
4	Et_3N	THF	12	54
5	PPh_3	DMF	12	NR
6	DBU	DMF	4	74
7	DBU	MeCN	4	49
8	DBU	THF	4	51
9	DBU	CH_2Cl_2	4	34

[a] Isolated yields.

Table 2. The solvent effects in the aza-Baylis–Hillman reaction of DIAD with phenyl acrylate catalyzed by DABCO



2a

Entry	Solvent	Time (h)	Yield (%)[a] (**2a**)
1	THF	12	71
2	DMF	12	81
3	MeCN	12	58
4	CH_2Cl_2	12	62

[a] Isolated yields.

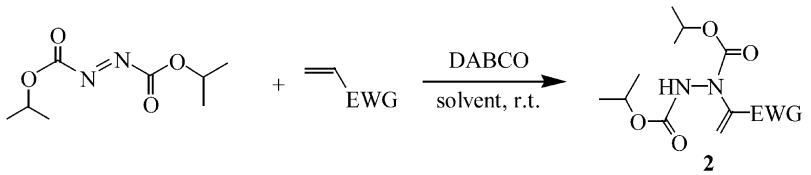
respectively. The best reaction condition for this type of aza-Baylis–Hillman reaction therefore is to carry out the reaction in THF or DMF using DABCO as a Lewis base promoter.

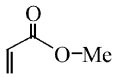
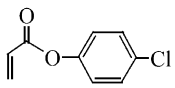
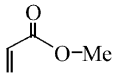
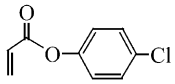
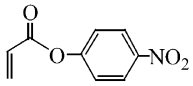
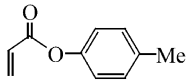
Under the optimized reaction conditions, we then extended the aza-Baylis–Hillman reactions of DIAD to other acrylates in THF or DMF. The results are summarized in Table 3. Using methyl acrylate as a Michael acceptor, we found that the corresponding aza-Baylis–Hillman adduct **2b** was formed in 24% in THF and 57% in DMF, respectively (Table 3, entries 1 and 3). Thus, if using DIAD as the substrate, the aza-Baylis–Hillman reaction with methyl acrylate can take place to give the corresponding aza-Baylis–Hillman adduct in moderate yield. For other phenyl acrylates such as *p*-chlorophenyl acrylate, *p*-nitrophenyl acrylate, and *p*-methylphenyl acrylate, the corresponding aza-Baylis–Hillman products **2c**, **2e**, **2f** were produced in good to high yields in DMF as well (Table 3, entries 5–7). For acrylonitrile, the corresponding adduct **2d** was also obtained in moderate yield (Table 3, entry 4). Their structures were determined by ^1H, ^{13}C NMR spectroscopic data, and HRMS or microanalyses. The relative configurations of C(O)–NHN and C(O)–NCN were disclosed by X-ray diffraction of **2f**.[9] The ORTEP draw of **2f** is shown in Figure 1 (its X-ray crystal data have been summarized in Section 3).

Additional work on the aza-Baylis–Hillman reaction of DEAD with acrylates or acrylonitrile was carried out under the optimized reaction conditions. The results are summarized in Table 4. As can be seen from Table 4, results similar to those from DIAD were obtained, although in the case of the reaction of DEAD with methyl acrylate only trace amount of adduct **3a** was obtained among polymeric materials (Table 3, entry 1). In contrast, using various phenyl acrylates as the Michael acceptors, the corresponding aza-Baylis–Hillman adducts **3c–f** were obtained in good to high yields under the same conditions (Table 3, entries 3–6). For acrylonitrile, the corresponding aza-Baylis–Hillman adduct **3b** was formed in moderate yield as well (Table 3, entry 2).

It should be emphasized here that only using dialkyl azocarboxylates such as DEAD or DIAD as the substrate, this type of aza-Baylis–Hillman reaction can take place. For other azo-compounds, for example, diphenyl azocarboxylate, 2,2′-azobisisobutyronitrile (AIBN), azobenzene, no reaction occurred under the same conditions (Scheme 1). It appears that a relatively stronger

Table 3. The aza-Baylis–Hillman reaction of DIAD with acrylates and acrylonitrile catalyzed by DABCO in THF and DMF



Entry	EWG	Solvent	Time (h)	Yield (%)[a] (**2**)
1		THF	12	**2b**, 24
2		THF	12	**2c**, 32
3		DMF	12	**2b**, 57
4		DMF	12	**2d**, 40
5		DMF	12	**2c**, 67
6		DMF	12	**2e**, 61
7		DMF	12	**2f**, 91

[a] Isolated yields.

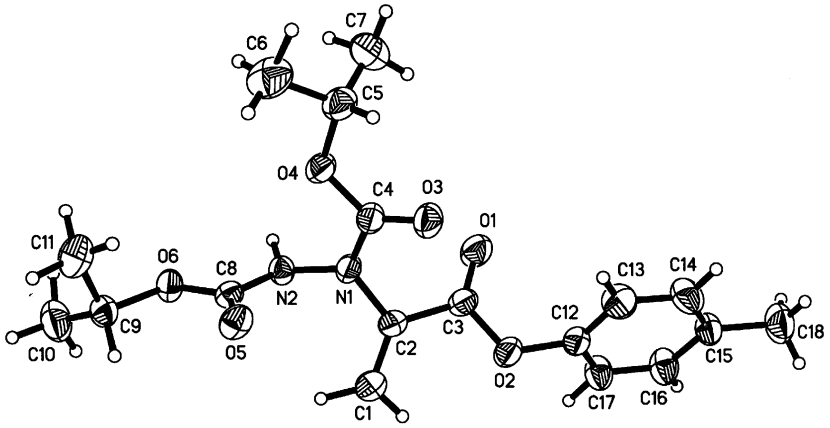


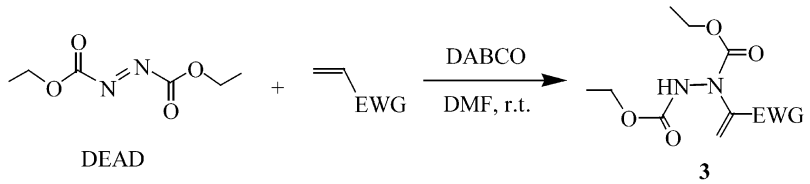
Figure 1. The ORTEP draw of **2f**.

electron-withdrawing group in the electrophile is required to initiate the nucleophilic attack of a zwitterionic species generated from Lewis base with α,β-unsaturated ketones or esters according to the typical reaction mechanism of Baylis–Hillman reaction.[2]

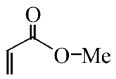
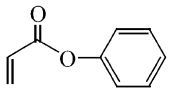
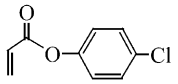
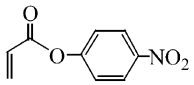
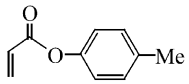
The plausible mechanism was described in Scheme 2.[2] The generated ammonium enolate **A** added to the N=N double bond to give the zwitterionic species **B** in *anti*-configuration[10] which underwent E2-elimination or intramolecular proton transfer and E1cb elimination from intermediated **C** to give the aza-Baylis–Hillman adduct and regenerate the nucleophilic promoter (Scheme 2).

In conclusion, we have found that the aza-Baylis–Hillman reaction of DIAD or DEAD with acrylates or acrylonitrile can take place in the presence of DABCO in DMF. For various phenyl acrylates, the corresponding

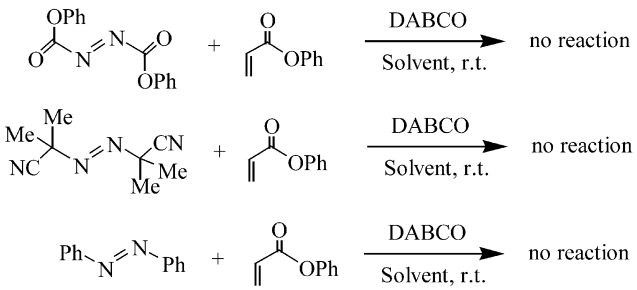
Table 4. The aza-Baylis–Hillman reaction of DEAD with acrylates and acrylonitrile in DMF catalyzed by DABCO



DEAD **3**

Entry	EWG	Time (h)	Yield (%)[a] (**3**)
1		12	**3a**, Trace
2		12	**3b**, 31
3		12	**3c**, 86
4		12	**3d**, 70
5		12	**3e**, 95
6		12	**3f**, 90

[a] Isolated yields.



Scheme 1.

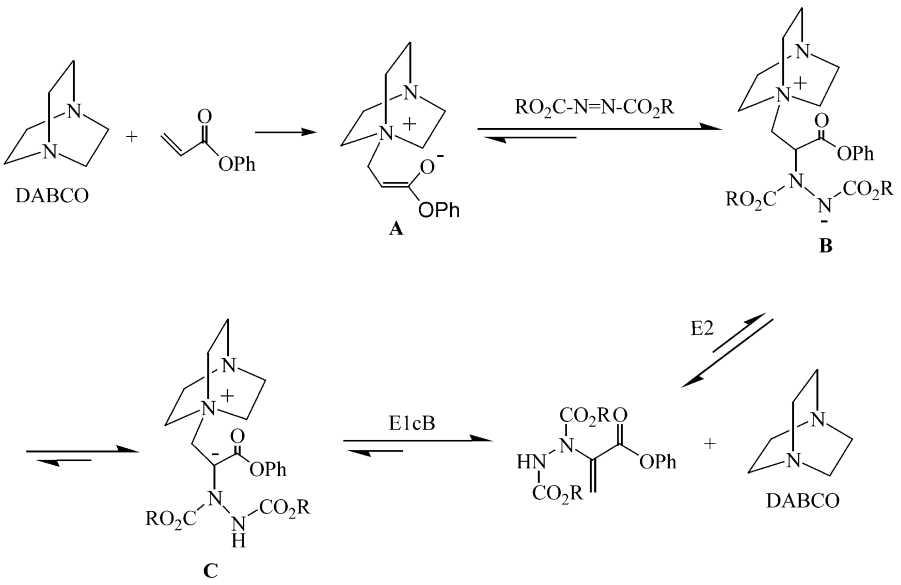
aza-Baylis–Hillman adducts **2** or **3** can be obtained in good to high yields. This finding can expand the scope and limitations of the previous literature of this type of aza-Baylis–Hillman reaction[7] and provide the corresponding α-hydrazino-α,β-unsaturated esters under mild conditions. Efforts are underway to elucidate the mechanistic details of this reaction and to disclose its scope and limitations. Work in this direction is currently in progress.

3. Experimental

3.1. General

MPs were obtained with a Yanagimoto micro melting point apparatus and are uncorrected. ^{1}H NMR spectra were recorded on a Bruker AM-300 spectrometer in $CDCl_3$ solution with tetramethylsilane (TMS) as internal standard; *J*-values are in Hz. Mass spectra were recorded with a HP-5989 instrument. Some of the solid compounds reported in this paper gave satisfactory CHN microanalyses with a Carlo-Erba 1106 analyzer. Commercially obtained reagents were used without further purification. All reactions were monitored by TLC with Huanghai GF_{254} silica gel coated plates. Flash column chromatography was carried out using 200–300 mesh silica gel at increased pressure. DIAD and DEAD were purchased from Aldrich. Co.

3.1.1. Typical reaction procedure of DIAD with phenyl acrylate at room temperature. To a Schlenk tube with DABCO (6 mg, 0.05 mmol) in DMF (0.5 mL) was added DIAD (101 mg, 99 μL, 0.50 mmol) and phenyl acrylate (74 mg, 0.50 mmol) and the reaction mixture was stirred for 12 h at room temperature (20 °C). The reaction mixture was washed with water (3×10 mL) and extracted with dichloromethane (2×10 mL). The organic layer was dried over anhydrous Na_2SO_4, the solvent removed under reduced pressure and the residue purified by silica gel column chromatography (eluent: EtOAc/petroleum=1:2) to give aza-Baylis–Hillman adduct **2a** (141 mg, yield 81%) as a white solid; mp 108–110 °C; IR (CH_2Cl_2) ν 1748 cm^{-1} (C=O); ^{1}H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.28–1.36 (12H, m, CH_3), 4.97–5.06 (2H, m, CH), 6.19 (1H, br. s, =CH), 6.44 (1H, br. s, =CH), 6.92 (1H, br. s, NH), 7.14–7.16 (2H, m, ArH), 7.24–7.30 (1H, m, ArH), 7.39–7.44 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 21.40, 21.47, 21.61, 21.67, 69.86, 71.17, 121.09, 121.36, 125.84, 129.22, 137.98, 150.26, 153.94, 155.59, 161.80; MS (EI) *m/e* 267 (M^+−83, 0.01), 264 (M^+−86, 5.72), 222



Scheme 2.

(M^+-128, 26.19), 173 (M^+-177, 28.93), 94 (M^+-256, 100), 43 (M^+-307, 66.87). Anal. calcd for $C_{17}H_{22}N_2O_6$ requires C, 58.27; H, 6.33; N, 8.00%. Found: C, 58.18; H, 6.29; N, 7.81%.

3.1.2. Aza-Baylis–Hillman adduct 1 (86 mg, yield 63%). A colorless oil; IR (CH_2Cl_2) ν 1717 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.19–1.29 (12H, m, CH_3), 2.33 (3H, s, CH_3), 4.87–4.97 (2H, m, CH), 5.91 (1H, br. s, ═CH), 5.96 (1H, br. s, ═CH), 7.25 (1H, br. s, NH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 21.39, 21.51, 21.66, 21.76, 25.77, 69.69, 71.05, 118.76, 146.19, 155.52, 162.46, 195.13; MS (EI) *m/e* 273 (M^++1, 1.75), 171 (M^+-101, 7.36), 144 (M^+-128, 16.35), 100 (M^+-172, 15.02), 43 (M^+-229, 100); HRMS calcd for $C_{12}H_{20}N_2O_5$: 272.1372. Found: 272.1355.

3.1.3. Aza-Baylis–Hillman adduct 2b (82 mg, yield 57%). A colorless oil; IR (CH_2Cl_2) ν 1717 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.24–1.35 (12H, m, CH_3), 3.81 (3H, s, OCH_3), 4.92–5.07 (2H, m, CH), 5.98 (1H, br. s, ═CH), 6.17 (1H, br. s, ═CH), 7.16 (1H, br. s, NH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 21.51, 21.59, 21.66, 21.76, 52.37, 69.87, 71.06, 122.73, 138.13, 154.14, 155.59, 163.92; MS (EI) *m/e* 289 (M^++1, 0.65), 205 (M^+-83, 8.72), 160 (M^+-128, 7.53), 116 (M^+-172, 9.96), 43 (M^+-245, 100); HRMS calcd for $C_{12}H_{20}N_2O_6$: 288.1321. Found: 288.1304.

3.1.4. Aza-Baylis–Hillman adduct 2c (128 mg, yield 67%). A white solid; mp 100–102 °C; IR (CH_2Cl_2) ν 1720 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.29–1.34 (12H, m, CH_3), 4.99–5.09 (2H, m, CH), 6.17 (1H, br. s, ═CH), 6.39 (1H, br. s, ═CH), 7.10–7.16 (2H, m, ArH), 7.27 (1H, br. s, NH), 7.35–7.41 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 21.69, 21.76, 22.48, 22.61, 70.06, 71.36, 122.61, 122.89, 129.27, 131.28, 137.87, 148.82, 153.93, 155.65, 161.67; MS (EI) *m/e* 385 (M^++1, 0.53), 298 (M^+-86, 2.23), 215 (M^+-169, 29.21), 173 (M^+-211, 51.81), 128 (M^+-256, 100), 43 (M^+-341, 52.22). Anal. calcd for $C_{17}H_{21}N_2O_6Cl$ requires C, 53.06; H, 5.50; N, 7.28%. Found: C, 53.18; H, 5.55; N, 7.15%.

3.1.5. Aza-Baylis–Hillman adduct 2d (51 mg, yield 40%). A colorless oil; IR (CH_2Cl_2) ν 1747 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.26–1.37 (12H, m, CH_3), 4.94–5.08 (2H, m, CH), 5.69 (1H, br, NH), 5.93 (1H, br, ═CH), 7.02 (1H, br, ═CH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 21.55, 21.63, 21.73, 25.44, 67.78, 70.54, 114.09, 118.57, 121.70, 152.26, 155.33; MS (EI) *m/e* 255 (M^+, 1.98), 154 (M^+-101, 8.91), 127 (M^+-128, 25.74), 83 (M^+-172, 15.84), 43 (M^+-212, 100); HRMS calcd for $C_{11}H_{17}N_3O_4$: 255.1219. Found: 255.1185.

3.1.6. Aza-Baylis–Hillman adduct 2e (120 mg, yield 61%). A colorless oil; IR (CH_2Cl_2) ν 1743 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.24–1.33 (12H, m, CH_3), 4.98–5.05 (2H, m, CH), 6.16 (1H, br. s, NH), 6.40 (1H, br. s, ═CH), 6.59 (1H, br. s, ═CH), 7.35–7.38 (2H, m, ArH), 8.27–8.33 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 21.50, 21.60, 21.70, 21.77, 70.54, 71.85, 115.48, 122.22, 125.09, 125.95, 129.51, 145.37, 155.01, 161.05, 162.66; MS (EI) *m/e* 397 (M^++2, 0.68), 396 (M^++1, 3.16), 309 (M^+-86, 3.66), 267 (M^+-128, 18.81), 140 (M^+-255, 14.08), 43 (M^+-352, 100); HRMS calcd for $C_{17}H_{21}N_3O_8+Na^+$: 418.1226. Found: 418.1221.

3.1.7. Aza-Baylis–Hillman adduct 2f (166 mg, yield 91%). A white solid; mp 104–105 °C; IR (CH_2Cl_2) ν 1751 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.24–1.30 (12H, m, CH_3), 2.35 (3H, s, CH_3), 4.97–5.02 (2H, m, CH), 6.17 (1H, br. s, ═CH), 6.31 (1H, br. s, ═CH), 6.90 (1H, br. s, NH), 7.00–7.03 (2H, m, ArH), 7.18–7.21 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 20.61, 21.51, 21.65, 21.71, 21.78, 69.89, 71.18, 120.77, 129.68, 129.74, 135.50, 138.04, 148.06, 154.01, 155.62, 162.02; MS (EI) *m/e* 365 (M^++1, 0.31), 278 (M^+-86, 2.35), 215 (M^+-149, 20.31), 173 (M^+-191, 32.71), 108 (M^+-256, 100). Anal. calcd for $C_{18}H_{24}N_2O_6$ requires C, 59.33; H, 6.64; N, 7.69%. Found: C, 59.38; H, 6.84; N, 7.63%.

The aza-Baylis–Hillman reaction of DEAD with acrylates or acrylonitrile was carried out in the same manner as that described above.

3.1.8. Aza-Baylis–Hillman adduct 3b (35 mg, yield 31%). A colorless oil; IR (CH_2Cl_2) ν 1740 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.25–1.39 (6H, m, CH_3), 4.20–4.41 (4H, m, CH_2), 5.73 (1H, s, NH), 5.99 (1H, br. s, ═CH), 6.82 (1H, br. s, ═CH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 14.15, 14.29, 62.90, 64.21, 114.02, 121.54, 125.45, 152.77, 155.53; MS (EI) *m/e* 228 (M^++1, 100), 184 (M^+−43, 49.00), 156 (M^+−71, 51.14), 129 (M^+−98, 26.58); HRMS calcd for $C_7H_8N_3O_3$ [M^+−OEt]: 182.0566. Found: 182.0528.

3.1.9. Aza-Baylis–Hillman adduct 3c (138 mg, yield 86%). A white solid; mp 100–103 °C; IR (CH_2Cl_2) ν 1748 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.26–1.33 (6H, m, CH_3), 4.21–4.30 (4H, m, CH_2), 6.23 (1H, br. s, ═CH), 6.49 (1H, br. s, ═CH), 7.02 (1H, br. s, NH), 7.13–7.16 (2H, m, ArH), 7.24–7.30 (1H, m, ArH), 7.38–7.45 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 14.24, 14.30, 62.22, 63.32, 121.21, 124.69, 126.06, 129.40, 137.77, 150.33, 154.60, 155.95, 161.86; MS (EI) *m/e* 323 (M^++1, 0.03), 229 (M^+−93, 100), 157 (M^+−165, 24.15), 129 (M^+−193, 60.31), 101 (M^+−221, 66.81). Anal. calcd for $C_{15}H_{18}N_2O_6$ requires C, 55.89; H, 5.63; N, 8.69%. Found: C, 55.62; H, 5.50; N, 8.60%.

3.1.10. Aza-Baylis–Hillman adduct 3d (125 mg, yield 70%). A white solid; mp 68–70 °C; IR (CH_2Cl_2) ν 1747 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.24–1.33 (6H, m, CH_3), 4.21–4.29 (4H, m, CH_2), 6.21 (1H, br. s, ═CH), 6.44 (1H, br. s, ═CH), 7.02 (1H, br. s, NH), 7.04–7.19 (2H, m, ArH), 7.33–7.39 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 14.20, 14.26, 62.22, 63.33, 122.61, 122.89, 129.40, 131.37, 137.53, 148.73, 154.45, 155.93, 161.60; MS (EI) *m/e* 311 (M^+−45, 1.43), 229 (M^+−127, 100), 129 (M^+−227, 68.48), 101 (M^+−255, 68.31). Anal. calcd for $C_{15}H_{17}N_2O_6Cl$ requires C, 50.50; H, 4.80; N, 7.85%. Found: C, 50.61; H, 4.72; N, 7.86%.

3.1.11. Aza-Baylis–Hillman adduct 3e (174 mg, yield 95%). An orange oil; IR (CH_2Cl_2) ν 1752 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.24–1.36 (6H, m, CH_3), 4.23–4.33 (4H, m, CH_2), 6.23 (1H, br. s, ═CH), 6.44 (1H, br. s, ═CH), 6.99 (1H, br. s, NH), 7.35 (2H, d, J=9.0 Hz, ArH), 8.31 (2H, d, J=9.0 Hz, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 14.52, 14.58, 62.63, 63.78, 122.57, 125.43, 137.80, 145.65, 154.68, 155.34, 156.28, 156.31, 161.30; MS (EI) *m/e* 295 (M^+−72, 6.50), 183 (M^+−184, 15.22), 139 (M^+−228, 100), 109 (M^+−358, 53.82), 65 (M^+−302, 82.12); HRMS calcd for $C_{15}H_{17}N_3O_8$+Na^+: 390.0913. Found: 390.0908.

3.1.12. Aza-Baylis–Hillman adduct 3f (151 mg, yield 90%). A white solid; mp 76–78 °C; IR (CH_2Cl_2) ν 1747 cm^{-1} (C═O); ^1H NMR ($CDCl_3$, 300 MHz, TMS) δ 1.24–1.32 (6H, m, CH_3), 2.35 (3H, s, CH_3), 4.20–4.28 (4H, m, CH_2), 6.21 (1H, br. s, ═CH), 6.46 (1H, br. s, ═CH), 6.99–7.03 (2H, m, ArH), 7.03–7.06 (1H, br. s, NH), 7.18–7.21 (2H, m, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz, TMS) δ 14.58, 14.64, 21.08, 62.51, 63.61, 121.20, 130.18, 130.20, 136.03, 148.42, 154.98, 156.29, 156.31, 162.38; MS (EI) *m/e* 337 (M^++1, 0.81), 229 (M^+−107, 100), 129 (M^+−207, 46.79), 101 (M^+−235, 43.41). Anal. calcd for $C_{16}H_{20}N_2O_6$ requires C, 57.13; H, 5.99; N, 8.33%. Found: C, 57.25; H, 6.03; N, 8.36%.

3.2. Crystallography

A suitable single crystal was mounted at the top of a glass capillary. Data were collected on a Rigaku AFC7R diffractometer with graphite-monochromated Mo Kα radition λ=0.71069 Å using the ω–2θ technique at 20 °C. The data were collected for Lorentz polarization effects. The structure was solved by direct methods and expanded using Fourier techniques.[11] The non-hydrogen atoms were refined anisotropically by full-matrix least squares. All hydrogen atoms were included in calculated position. All calculations were performed using the TEXSAN crystallographic software package. Its crystal structure has been deposited at the Cambridge Crystallographic Data Center and has been allocated the deposition number: CCDC 215759.

Crystal data of **2f**: empirical formula: $C_{18}H_{24}N_2O_6$; formula weight: 364.39; crystal color, habit: colorless, prismatic; crystal dimensions: 0.451×0.390×0.123 mm^3; crystal system: monoclinic; lattice type: primitive; lattice parameters: a=11.2800(9) Å, b=9.2104(8) Å, c=19.2985(16) Å, α=90°, β=98.879°, γ=90°, V=1981.0(3) $Å^3$; space group: $P2(1)/c$; Z=4; D_{calc}=1.222 g/cm^3; F_{000}=776; diffractometer: Rigaku AFC7R; residuals: R; Rw: 0.0449, 0.0805.

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