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Tetrahedron
Tetrahedron 63 (2007) 8305–8310

Tributylphosphine, excellent organocatalyst for conjugate additions of non-nucleophilic *N*-containing compounds

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Received 23 April 2007; revised 18 May 2007; accepted 22 May 2007
Available online 26 May 2007

Abstract—Conjugate additions of non-nucleophilic *N*-containing compounds such as amides, thioamides, sulfonamides, and electron-poor anilines with different Michael acceptors can be promoted through the use of tributylphosphine. The range of useful pK_a's of nucleophiles has been established (pK_a<25) and new insights into the mechanism proposed.

1. Introduction

Conjugate additions constitute a powerful method for the formation of carbon–carbon[1] and carbon–heteroatom bonds. Carbon–nitrogen bonds are especially valuable since the resulting functionality can be readily transformed. For instance, the β-aminocarbonyl group is a common moiety in biologically active natural products such as alkaloids. To avoid typical disadvantages resulting from the presence of basic or acid catalysis, a variety of methods have been used for the reaction of amines with poor alkenes as, for example, promotion through the use of stoichiometric $CeCl_3\cdot 7H_2O$–NaI system supported in silica gel[2] or $LiClO_4$.[3] Other research groups have described that conjugate addition of amines of poor alkenes can be catalysed using Lewis acids such as $Bi(OTf)_3$,[4] $Bi(NO)_3$[5] or $ZrOCl_2\cdot 8H_2O$.[6] From the point of view of recovering the catalyst the use of Cu–Al hydrotalcite[7] is proposed. Recently a green approach using β-cyclodextrin in water[8] or ionic liquids[9] has been developed. Microwave-promoted synthesis of *N*-aryl β-amino-esters have been recently described.[10] Moreover asymmetric aza-Michael reactions can be promoted using a Mg(II), Cu(II), Ni(II) or Ti(IV) catalyst containing different chiral ligands.[11] While aza-Michael-type addition reactions of amines to α,β-unsaturated substrates are well known, we found no general method for non-nucleophilic *N*-containing compounds such as amides, thioamides, sulfonamides, urea, and electron-poor anilines. Few isolated examples can be found: amides react efficiently with enones under a catalytic amount of $Pd(PhCN)_2Cl_2$[12] and with unsaturated esters under a CsF–$Si(OEt)_4$ system;[13] intramolecular Michael addition of urea to unsaturated esters has been described in the presence of NaOH;[14] conjugate addition of 4-nitroaniline and carbamic acid methyl ester to α,β-unsaturated compounds can be mediated by $RuCl_3$ in poly(ethylene glycol).[15]

Recently the scientific community has begun to appreciate the great potential of organocatalysis,[16] which is defined as the acceleration of chemical reactions with a substoichiometric amount of an organic compound, and phosphines have been recognized as a useful nucleophilic organocatalyst.[17] We have previously described that triphenylphosphine and tributylphosphine are excellent catalysts for the reaction of β-dicarbonyl compounds and electron-poor olefins.[18] The mechanism involves the so-called nucleophilic phosphine catalysis (NPC), initiated by the nucleophilic attack of the phosphine to the β-position of an activated alkene or alkyne. The generated α-carbanion then reacts as a nucleophile or as a base. The reaction of the phosphonium ylide as a base affords the conjugated base of the dicarbonyls (Fig. 1) that triggers the propagation steps as indicated. As an extension we now want to describe a study on the use of tributylphosphine for the conjugate addition of a selection of non-nucleophilic *N*-containing compounds. Moreover some NMR experiments have been carried out to bring insights into the proposed mechanism.

2. Results and discussion

We selected a series of non-nucleophilic *N*-containing compounds that were chosen as to embrace a broad diversity of pK_a's (range of pK_a's 14–27 in dimethyl sulfoxide,[19] Fig. 2) and studied their conjugate additions to different activated alkenes under the presence of a catalytic amount

Keywords: Phosphine; Conjugate addition; Organocatalyst; C–N bond; Mechanism.
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0040–4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.05.088

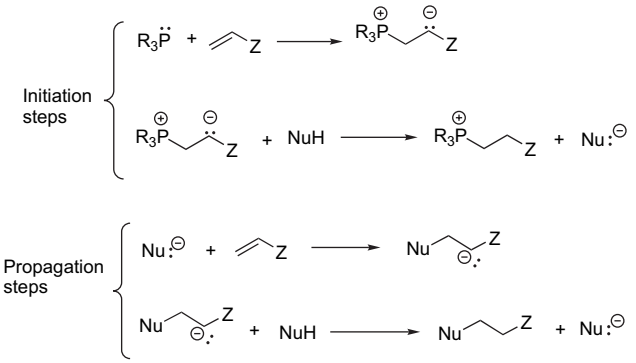


Figure 1. Mechanism of nucleophilic phosphine catalysis.

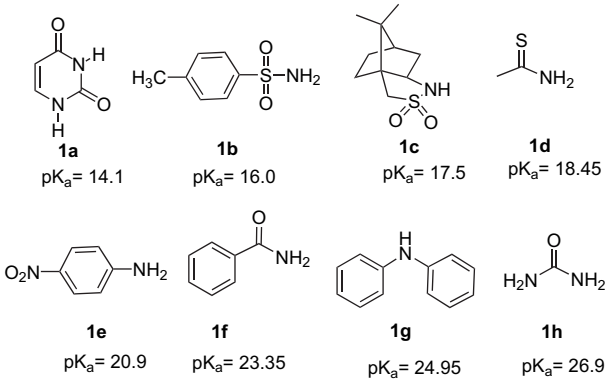
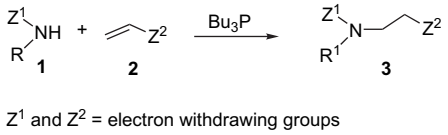


Figure 2. pK_a's in dimethyl sulfoxide solution for nucleophiles **1**.

of tributylphosphine (Scheme 1). We have previously established that tributylphosphine is more active[18b] than triphenylphosphine corresponds to the higher nucleophilicity parameters *N* [Bu_3P (15.49), Ph_3P (14.33)].[20] All conjugate additions were carried out in acetonitrile, a relative polar solvent. Recently, Liu and co-workers[21] have found that the solvent exerts profound effects on the basicity of phosphines and reported the basicity of a huge number of phosphines in acetonitrile [Bu_3PH^+ (pK_a=16.2), Ph_3PH^+ (pK_a=6.5)], tributylphosphine being more basic than triphenylphosphine.



Scheme 1. Conjugate addition catalyzed by phosphines.

The results obtained are reported in Tables 1 and 2. All reactions were carried out in the presence of a 10% mol equiv of Bu_3P unless stated otherwise. Uracil **1a** reacted at room temperature with an excess of butenone and less active acrylonitrile to obtain di-*N*-alkylated compounds **3aaa** (95% yield) and **3abb** (89% yield), respectively. In addition sulfonamide **1b** was tested with acrylonitrile and ethyl acrylate affording products **3bbb** and **3bcc** in high yields at room temperature. Also Oppolzer's sultam reacted with ethyl acrylate and the *N*-alkylated compound **3cc** was obtained at room temperature in a high 85% yield. Moreover, thioacetamide **1d** reacted with **2b** and **2c** to afford di-*N*-alkylated adducts, albeit the excess of electrophile mono-alkylated adducts **3db** (4%) and **3dc** (9%) being also isolated although in very low yields. In addition, compounds **4bb** and **4cc** (Scheme 2) being identified by GC–MS (**4bb**: MS (*m*/*z*) 140 (M^+), 100, 54; **4cc**: MS (*m*/*z*) 243 (M^+), 160, 143) as subproducts of the reactions corresponding to entries 6 and 7 of Table 2, respectively. Formation of compounds **4** can be explained through the mechanism proposed in Scheme 2, which is based on the resonance stabilization of the thioacetamide conjugated base.

Less acidic 4-nitroaniline **1e** reacted with **2b** and **2c** although yields were slightly lower. Then reactions of acetamide **1f** with acrylonitrile and diethyl vinylphosphonate were also studied. In the case of acrylonitrile the mono-adduct was identified but could not be completely purified. In the contrary, mono and di-adducts were isolated and purified in the reactions with **2d**. Even diphenylamine reacted at 140 °C to afford 29% of **3gd**. However urea (pK_a=26.9) was inert in the same reaction conditions using **2c** and **2d** as Michael acceptors.

Some general trends can be established from a perusal of all the results. First, yields are excellent for nucleophiles with a pK_a<20 (DMSO). Additionally, larger quantities of mono-adduct compounds are obtained from less active nucleophiles. Furthermore it is obvious that conjugate additions are slower using less active nucleophiles and in these cases the formation of dimers coming from the Michael acceptor becomes to be a competitive reaction. In fact the phosphate-catalyzed dimerization of electron-deficient alkenes was first reported by Rauhut and Currier in 1963[22] and more recently has been used by Krische[23] and coworkers in cycloisomerizations and the group of Roush[24] in the vinylogous intramolecular Morita–Baylis–Hillman reaction.

In order to obtain new insights to the mechanism we conducted some ^{31}P NMR spectroscopy experiments. ^{31}P chemical shift for Bu_3P in CD_3OD is −32.5 whereas after addition of butenone to the NMR tube the δ changed to 30.5, typical chemical shift of a phosphonium salt. This suggested the presence of the β-phosphonium ketone **5**. First reaction of Scheme 3 illustrates this process. An equivalent of this phosphonium ketone was independently prepared through an alternative route[25] (reaction 2, Scheme 3) in order to compare chemical shifts. Compound **6** was obtained from addition of tetrabutylammonium iodide to butenone followed by reaction with tributylphosphine. ^{31}P chemical shift value for **6** was 32.7. The match on the chemical shifts suggests that the initial attack of the phosphine on the olefin generates a phosphonium β-ylide being quickly protonated in hydroxylic solvents. In the case of the conjugate addition, since there is an anhydrous media this β-ylide causes deprotonation of the nucleophile giving conjugated base, which triggers the propagation steps indicated in Figure 3 as a cycle (pathway 1). However, we envisaged another possibility consisting of direct attack of conjugate base to phosphonium cation (pathway 2). Experiments with the sodium salts of 1,3-diphenyl-1,3-propandione and 1,3-cyclohexandione with phosphonium salt **6** permitted

Table 1. Preparation of products **3** (Scheme 1)

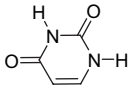
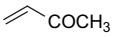
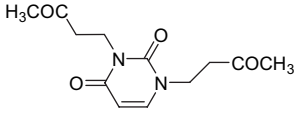
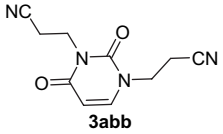
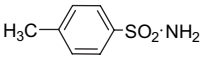
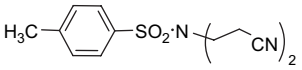
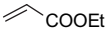
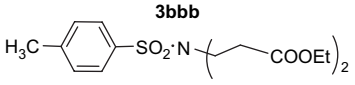
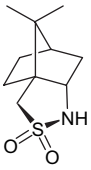
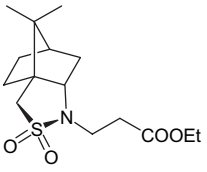
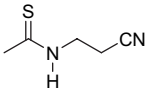
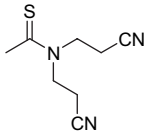
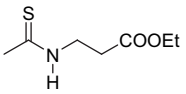
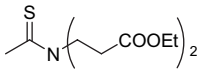
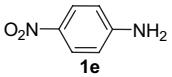
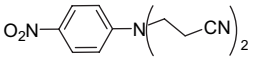
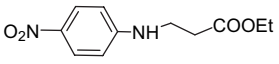
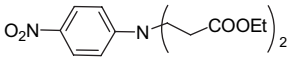
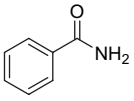
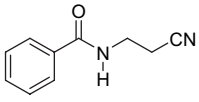
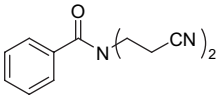
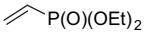
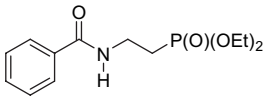
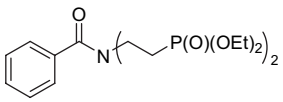
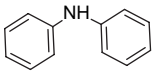
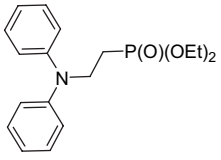
Entry	Nucleophile	Electrophile	Products
1	 **1a**	 **2a**	 **3aaa**
2	**1a**	 **2b**	 **3abb**
3	 **1b**	**2b**	 **3bbb**
4	**1b**	 **2c**	 **3bcc**
5	**2c**		
	 **1c**		 **3cc**
6	 **1d**	**2b**	 **3db**  **3dbb**
7	**1d**	**2c**	 **3dc**  **3dcc**
8	 **1e**	**2b**	 **3ebb**
9	**1e**	**2c**	 **3ec**  **3ecc**
10	 **1f**	**2b**	 **3fb**  **3fbb**
11	**1f**	 **2d**	 **3fd**  **3fdd**
12	 **1g**	**2d**	 **3gd**

Table 2. Experimental conditions for the preparation of compounds **3** in CH_3CN (Scheme 1)

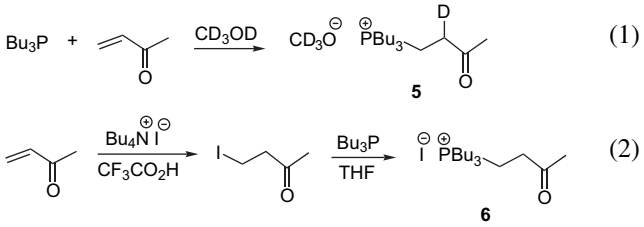
Entry	Product	Molar ratio 2:1	Temp (°C)	Time[a] (h)	Yield (%) **3**
1	**3aaa**	2.8	rt	3.5	95
2	**3abb**	5.9	rt	22	89
3	**3bbb**	6.0	rt	6	76
4	**3bcc**	3.0	rt	18	52
5	**3cc**	5.9	rt	24	85
6	**3db/3dbb**	5.7	rt	23	4[b]/50
7	**3dc/3dcc**	5.8	rt	3	9[b]/43
8	**3ebb**	6.1	rt	20	71
9[c]	**3ec/3ecc**	9.4	reflux	30.5	2[b]/56
10	**3fb/3fbb**	5.9	rt	142	7[b]/27
11	**3fd/3fdd**	2.2	reflux	5	24[b]/51
12	**3gd**	1.5	140[d]	14	29

[a] Not optimized.
[b] Mono-adduct.
[c] Bu_3P (20%) was used.
[d] Closed reactor.

us to reject this mechanism due to the fact that no nucleophilic substitution of the tributylphosphine by the conjugate bases of the β-diketones was observed.

3. Conclusion

In summary, we discovered a novel phosphine-catalyzed aza-Michael type reaction of non-nucleophilic *N*-containing compounds. The procedure is very simple and the scope is huge not only from the point of view of nucleophiles (amides, thioamides, sulfonamides, and electron-poor anilines) but also electrophiles (butenone, acrylonitrile, ethylacrylate, and diethylvinylphosphonate). The range of useful pK_a's of nucleophiles has been established (pK_a <25). The investigation of the mechanism permitted us to demonstrate that a phosphonium β-ylide was formed, which deprotonates



Scheme 3. Synthesis of phosphonium salts **5** and **6**.

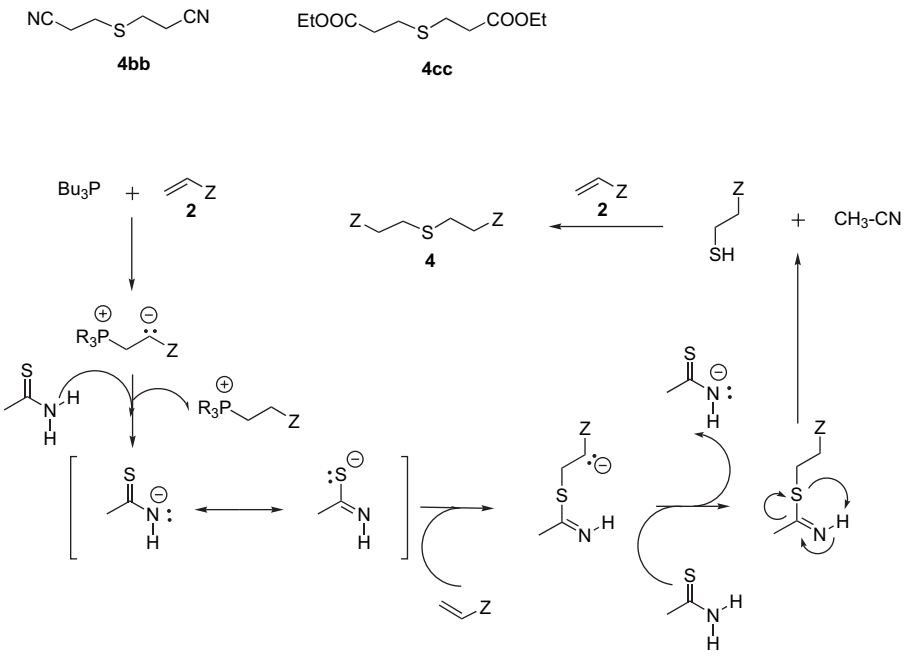
the nucleophile that triggers the propagation steps, no direct reaction with the phosphonium salt being observed.

4. Experimental

4.1. General procedure

A mixture of benzamide **1f** (0.518 g, 4.30 mmol), diethyl vinylphosphonate **2d** (1.4 mL, 9.4 mmol), and Bu_3P (104 μL, 0.417 mmol) in anhydrous CH_3CN (1.5 mL) was stirred in a Schlenk tube under nitrogen atmosphere and reflux temperature. After 5 h the solvent was evaporated and the residue was chromatographed through silica gel with ethyl acetate/methanol (9.5:0.5) to afford **3fd** and **3fdd**. Both products were further purified by chromatography with ethyl acetate/diethyl ether (1:1) and diethyl ether/methanol (9.5:0.5), respectively, to afford 0.292 g of pure **3fd** in 24% yield and 0.977 g of pure **3fdd** in 51% yield.

4.1.1. *N*-[2-(Diethoxyphosphoryl)ethyl]benzamide (3fd). ^1H NMR (250 MHz, $CDCl_3$): δ=1.32 (t, J=7.0 Hz, 6H), 2.07 (dt, J=17.2, 6.3 Hz, 2H), 3.76 (dt, J=22.4, 6.3 Hz, 2H), 4.06–4.19 (m, 4H), 7.29 (br s, 1H), 7.38–7.51 (m, 3H), 7.79–7.83 (m, 2H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=16.7 (d, J=6.4 Hz), 25.6 (d, J=139.2 Hz), 34.1 (d,



Scheme 2. Possible mechanism for the formation of compounds **4**.

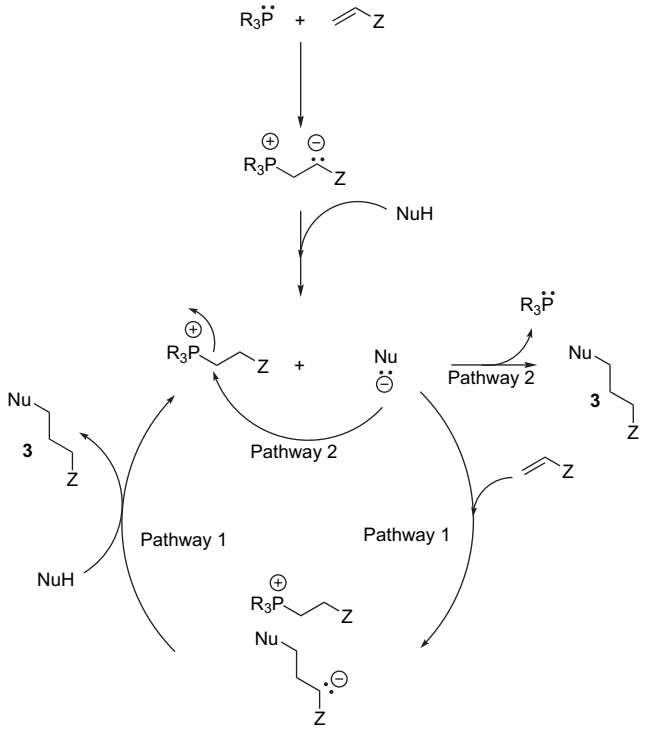


Figure 3. Possible competition between pathways 1 and 2.

J=6.6 Hz), 62.2 (d, J=6.1 Hz), 127.2, 128.8, 131.7, 134.4, 167.3. IR (ATR): ν=3295, 2981, 1640, 1538, 1924, 1221 cm^{-1}. HRMS (ESI): m/z calcd for $C_{13}H_{20}NO_4P$ $[M]^+$: 285.1130; found $[M+H]^+$: 286.1203.

4.1.2. *N*,*N*-Bis[2-(diethoxyphosphoryl)ethyl]benzamide (3fdd). ^1H NMR (250 MHz, DMSO) T=373 K: δ=1.28 (t, J=7.0 Hz, 12H), 2.05–2.19 (m, 4H), 3.56–3.67 (m, 4H), 4.04 (dq, J=8.6, 7.0 Hz, 8H), 7.41–7.50 (m, 5H). ^{13}C NMR (62.5 MHz, DMSO) T=373 K: δ=16.2 (d, J=5.4 Hz), 24.9 (d, J=134.9 Hz), 41.6, 61.4 (d, J=6.4 Hz), 126.6, 128.4, 129.3, 137.1, 170.8. IR (ATR): ν=2981, 2907, 1633, 1239, 1022, 956 cm^{-1}. HRMS (ESI): m/z calcd for $C_{19}H_{33}NO_7P_2$ $[M]^+$: 449.1732; found $[M+H]^+$: 450.1805.

4.1.3. 1,3-Bis(3-oxobutyl)uracil (3aaa).[26] ^1H NMR (250 MHz, $CDCl_3$): δ=2.12 (s, 3H), 2.13 (s, 3H), 2.71 (t, J=7.5 Hz, 2H), 2.89 (t, J=5.8 Hz, 2H), 3.89 (t, J=5.8 Hz, 2H), 4.12 (t, J=7.5 Hz, 2H), 5.62 (d, J=8.0 Hz, 1H), 7.36 (d, J=8.0 Hz, 1H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=30.1, 30.3, 36.6, 41.3, 41.9, 45.3, 101.2, 144.4, 151.5, 163.1, 206.7, 206.8. IR (ATR): ν=3093, 2964, 1701, 1648, 1455, 1355, 1226, 1165, 804, 767 cm^{-1}.

4.1.4. 1,3-Bis(2-cyanoethyl)uracil (3abb).[27] ^1H NMR (250 MHz, $CDCl_3$): δ=2.74 (t, J=7.0 Hz, 2H), 2.81 (t, J=6.2 Hz, 2H), 3.99 (t, J=6.2 Hz, 2H), 4.23 (t, J=7.0 Hz, 2H), 5.79 (d, J=7.9 Hz, 1H), 7.27 (d, J=7.9 Hz, 1H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=16.4, 17.7, 36.8, 46.3, 102.5, 117.1, 117.4, 143.0, 151.1, 162.3. IR (ATR): ν=2976, 2244, 1704, 1649, 1451, 1345, 1228, 802, 764 cm^{-1}.

4.1.5. *N*,*N*-Bis[(2-cyanoethyl)]-4-methylbenzenesulfonamide (3bbb). Mp 102–104 °C (lit. mp 100–102 °C).[28] ^1H NMR (250 MHz, $CDCl_3$): δ=2.45 (s, 3H), 2.74 (t, J=7.0 Hz, 4H), 3.44 (t, J=7.0 Hz, 4H), 7.35 (d, J=8.3 Hz, 2H), 7.70 (d, J=8.3 Hz, 4H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=19.2, 21.8, 46.3, 117.8, 130.5, 134.9, 145.1. IR (ATR): ν=2944, 2254, 1597, 1340, 1159, 1112, 712, 698 cm^{-1}.

4.1.6. *N*,*N*-Bis[(2-ethoxycarbonyl)ethyl]-4-methylbenzenesulfonamide (3bcc).[29] ^1H NMR (250 MHz, $CDCl_3$): δ=1.23 (t, J=7.1 Hz, 6H), 2.41 (s, 3H), 2.61 (t, J=7.3 Hz, 4H), 3.40 (t, J=7.3 Hz, 4H), 4.11 (t, J=7.3 Hz, 4H), 7.30 (d, J=7.3 Hz, 4H), 7.68 (d, J=7.3 Hz, 4H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=14.3, 21.7, 34.6, 45.2, 61.0, 127.4, 129.9, 136.1, 143.7, 171.4. IR (ATR): ν=2981, 1727, 1598, 1314, 1184, 1155, 690 cm^{-1}.

4.1.7. (2*R*)-*N*-[2-(Ethoxycarbonyl)ethyl]bornano-10,2-sultame (3cc). ^1H NMR (250 MHz, $CDCl_3$): δ=0.88 (s, 3H), 1.07 (s, 3H), 1.22 (t, J=7.1 Hz, 3H), 1.23–1.43 (m, 2H), 1.65 (dd, J=8.0, 12.7 Hz, 1H), 1.75–1.90 (m, 3H), 2.02–2.10 (m, 1H), 2.60 (ddd, J=5.6, 7.4, 16.5 Hz, 1H), 2.76 (dt, J=7.6, 16.5 Hz, 1H), 3.03 (dd, J=4.5, 8 Hz, 1H), 3.10 (s, 2H), 3.14 (dt, J=7.6, 13.7 Hz, 1H), 3.32 (ddd, J=5.6, 7.1, 13.7 Hz, 1H), 4.11 (q, J=7.1 Hz, 1H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=16.8, 22.4, 22.6, 29.0, 34.0, 34.7, 36.9, 40.3, 45.9, 48.8, 50.9, 51.0, 61.4, 67.8, 167.5. IR (ATR): ν=3622, 3554, 3447, 2955, 1730, 1374, 1303, 1151, 1120, 788, 682 cm^{-1}. Anal. Calcd for $C_{15}H_{25}NO_4S$: C, 57.12; H, 7.99; N, 4.44. Found: C, 57.45; H, 7.99; N, 4.30. $[\alpha]_D$ −79.4 (c 1.00, $CHCl_3$).

4.1.8. *N*,*N*-Bis(2-cyanoethyl)thioacetamide (3dbb). ^1H NMR (250 MHz, $CDCl_3$): δ=2.75 (s, 3H), 2.76 (t, J=6.8 Hz, 2H), 3.02 (t, J=6.2 Hz, 2H), 4.07 (t, J=6.8 Hz, 2H), 4.22 (t, J=6.2 Hz, 2H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=14.7, 17.3, 32.9, 49.1, 49.5, 116.5, 118.4, 202.9. IR (ATR): ν=2996, 2249, 1453, 1359, 1274, 1218, 1004 cm^{-1}. Anal. Calcd for $C_8H_{11}N_3S$: C, 52.93; H, 6.12; N, 23.18. Found: C, 56.80; H, 6.00; N, 22.95.

4.1.9. *N*,*N*-Bis[2-(ethoxycarbonyl)ethyl]thioacetamide (3dcc). ^1H NMR (250 MHz, $CDCl_3$): δ=1.24 (t, J=7.1 Hz, 3H), 1.26 (t, J=7.1 Hz, 3H), 2.65 (t, J=7.6 Hz, 2H), 2.66 (s, 3H), 2.84 (t, J=7.0 Hz, 2H), 3.92 (t, J=7.6 Hz, 2H), 4.09–4.20 (m, 6H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=14.4, 31.2, 32.8, 33.1, 48.9, 49.2, 61.0, 61.5, 170.5, 172.0, 201.0. IR (ATR): ν=2980, 2937, 1724, 1501, 1454, 1419, 1375, 1181, 1014 cm^{-1}. Anal. Calcd for $C_{18}H_{21}NO_4S$: C, 52.34; H, 7.69; N, 5.09. Found: C, 52.27; H, 7.91; N, 4.82.

4.1.10. *N*,*N*-Bis(2-cyanoethyl)-4-nitroaniline (3ebb). Mp 159–161 °C (lit. mp 163–164 °C).[29] ^1H NMR (250 MHz, $CDCl_3$): δ=2.85 (t, J=6.9 Hz, 4H), 3.88 (t, J=6.9 Hz, 4H), 7.01 (d, J=9.5 Hz, 2H), 8.08 (q, J=9.5 Hz, 2H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=15.7, 46.3, 112.3, 119.5, 126.4, 137.7, 152.2. IR (ATR): ν=2249, 1588, 1492, 1315, 1112, 834, 751 cm^{-1}.

4.1.11. *N*-[2-(Ethoxycarbonyl)ethyl]-4-nitroaniline (3ec). Mp 72–75 °C .^1H NMR (250 MHz, $CDCl_3$): δ=1.26 (t, J=7.1 Hz, 3H), 2.63 (t, J=6.1 Hz, 2H), 3.53 (t, J=6.1 Hz, 2H), 4.16 (q, J=7.1 Hz, 2H), 4.94 (br s, 1H), 6.54 (dd,

J=7.0, 2.1 Hz, 2H), 8.08 (dd, J=7.0, 2.1 Hz, 2H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=14.4, 33.8, 39.0, 61.3, 111.4, 126.7, 138.6, 153.1, 172.2. IR (ATR): ν=3367, 2921, 1705, 1612, 1596, 1311, 1113 cm^{-1}. Anal. Calcd for $C_{11}H_{14}N_2O_4$: C, 55.46; H, 5.92; N, 11.76. Found: C, 54.45; H, 5.96; N, 11.41.

4.1.12. *N*,*N*-Bis[2-(ethoxycarbonyl)ethyl]-4-nitroaniline (3ecc). ^{1}H NMR (250 MHz, $CDCl_3$): δ=1.24 (t, J=7.1 Hz, 6H), 2.61 (t, J=7.2 Hz, 4H), 3.76 (t, J=7.2 Hz, 4H), 4.13 (q, J=7.1 Hz, 4H), 6.63 (dd, J=7.4, 2.1 Hz, 2H), 8.10 (dd, J=7.4, 2.1 Hz, 2H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=14.4, 32.4, 47.1, 61.2, 110.9, 126.6, 137.9, 151.8, 171.5. IR (ATR): ν=2981, 1724, 1592, 1308, 1181, 1111 cm^{-1}. Anal. Calcd for $C_{16}H_{22}N_2O_6$: C, 56.80; H, 6.55; N, 8.28. Found: C, 56.80; H, 6.58; N, 8.18.

4.1.13. *N*,*N*-Bis(2-cyanoethyl)benzamide (3fbb). Mp 101–104 °C (lit. mp 106–108 °C).[30] ^{1}H NMR (250 MHz, DMSO): δ=2.87 (t, J=6.7 Hz, 4H), 3.70 (t, J=6.7 Hz, 4H), 7.45–7.54 (m, 5H). ^{13}C NMR (62.5 MHz, DMSO): δ=16.7, 119.1, 127.3, 129.2, 130.2, 136.4, 171.9. IR (ATR): ν=2967, 2246, 1630, 1417, 1255, 1024, 701 cm^{-1}.

4.1.14. Diethyl[2-(diphenylamino)ethyl]phosphonate (3gd). ^{1}H NMR (250 MHz, $CDCl_3$): δ=1.32 (t, J=7.1 Hz, 6H), 2.08–2.22 (m, 2H), 3.98–4.14 (m, 6H), 6.93–7.01 (m, 6H), 7.24–7.30 (m, 4H). ^{13}C NMR (62.5 MHz, $CDCl_3$): δ=16.5 (d, J=6.2 Hz), 23.9 (d, J=134.1 Hz), 46.0, 61.7 (d, J=6.6 Hz), 121.0, 121.7, 129.4, 147.1. IR (ATR): ν=2979, 2904, 1858, 1493, 1242, 1023, 954 cm^{-1}. HRMS (ESI): m/z calcd for $C_{18}H_{24}NO_3P$ $[M]^+$: 333.1494; found $[M+H]^+$: 334.1567.

4.1.15. Tributyl(3-oxobutyl)phosphonium iodide (6). A mixture of butenone (0.84 mL, 0.01 mmol) and tetrabutylammonium iodide (5.2 g, 0.014 mmol) in distilled CF_3CO_2H (10 mL) was stirred in a Schlenk tube under nitrogen atmosphere at room temperature. After 1 h a mixture of 30 mL of water and 30 mL of pentane is added to the reaction mixture. The organic layer was then dried and evaporated obtaining 0.815 g (41% yield) of 4-iodobutan-2-one. No purification was required. Then a mixture of 4-iodobutan-2-one (0.353 g, 0.0018 mmol) and tributylphosphine (1.4 mL, 0.005 mmol) in 3.5 mL of anhydrous THF was stirred in a Schlenk tube under nitrogen atmosphere at room temperature for 20 h. Solvent was evaporated off and water was added to the residue. Extraction with diethyl ether (4×30 mL), the aqueous layer was evaporated and the residue dried at 50 °C to afford 0.437 g (61%) of compound **6**. ^{31}P NMR (101 MHz, CD_3OD): δ=32.7. ^{1}H NMR (250 MHz, CD_3OD): δ=1.04 (t, J=7 Hz, 9H), 1.48–1.68 (m, 12H), 2.28 (s, 3H), 2.22–2.35 (m, 6H), 2.48 (dt, J= 7.2, 13 Hz, 2H), 3.02 (dt, J=7.2, 12.2 Hz, 2H). HRMS: m/z calcd for $[M]^+$: 273.2342; found: 273.2338.

Acknowledgements

Financial support from Ministry of Education and Science of Spain (Project CTQ2005-04968-C02-01 and predoctoral scholarship to E.P.) and *Generalitat de Catalunya* (Project 2005SGR00305 and predoctoral scholarship to C.G.) is gratefully acknowledged.

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