Trichlorolanthanoid(cat.)/zinc system promoted cyclodimerisation of arylidenemalononitriles and arylmethylenecyanoacetates

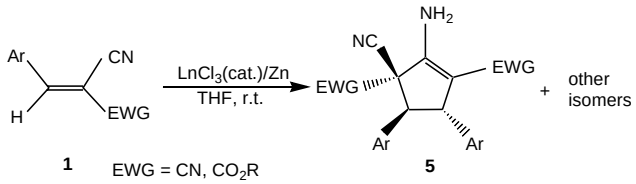
Weike Su* and Bibo Yang

College of Pharmaceutical Sciences, Zhejiang University of Technology, Hangzhou, Zhejiang, 310014, P.R. China

A trichlorolanthanoid(cat.)/zinc system has been found to promote cyclodimerisation of arylidenemalononitriles and arylideneanoacetates to give highly functionalised cyclopentene derivatives in high yield and stereoselectivity.

Keywords: cyclodimerisation, arylidenemalononitriles, arylmethylenecyanoacetates

The cyclodimerisation of carbonyl derivatives promoted by active metals and their compounds is one of the most valuable methods for forming carbon–carbon bonds.[1] In general, the carbonyl derivatives are aldehydes, ketones, carboxylic esters, acid chlorides or imines and the active metals are alkali or alkaline earth metals.[2] Fujiwara and coworkers have reported that the cyclodimerisation of α, β-unsaturated carbonyl compounds promoted by ytterbium metal alone and trichlorolanthanoid(cat.)/zinc can give cyclopentanol derivatives.[3] Ding *et al.* have reported hydroperfluoroalkylation of alkenes using a $R_f/YbCl_3$(cat.)/Zn system.[4] Recently, there are some reports on the reductive dimerisation and reductive dimerisation cyclisation of α, β-unsaturated carbonyl compounds and α, β-unsaturated amides.[5] Here we wish to report the cyclodimerisation of arylidenemalononitriles and arylmethylenecyanoacetates promoted by a trichlorolanthanoid(cat.)/zinc system at room temperature to afford highly functionalised cyclopentene derivatives in both high yields and stereoselectivities (Scheme 1).



Scheme 1

Table 1 summarises our results on the cyclodimerisation of a number of substrates. In all the reactions, the cleavage takes place at the C≡N bond, rather than a C=O bond and these reactions are highly regio-and stereo selective. Although the product stereoisomeric cyclic hydro-dimers could not be separated by TLC, the *trans*-isomers (EWG = CN) and *trans*, *trans*-isomers (EWG = CO_2R) could be separated as pure compounds from mixtures of their isomers by fractional crystallisation. From Table 1, we found that a catalytic amount of trichlorolanthanoid was enough to complete the reactions, and the yields and stereoselectivities were slightly higher when $YbCl_3$ was used (Entries a, e and f). Probably, this result can be attributed to the stability of the electronic configurations of Ln^{2+}, filled f^{14} (Yb^{2+}) and half filled f^6 (Sm^{2+}). This seems to indicate that the reaction is caused by Ln (II) species. The possible mechanism is shown in Scheme 2.[3, 7] $LnCl_3$ is reduced by Zn to give low-valent species such as $LnCl_2$. Then, an electron is transferred from $LnCl_2$ to the substrate **1** by a single-electron transfer (SET) process results in the formation of a radical anion **2**; radical anion **2** then attacks another substrate to form a carbon–carbon bond and generates **3**. The latter undergoes reaction to form another carbon–carbon bond and to produce intermediate **4**. Then, product **5** and other isomers were obtained after protonation and tautomerisation.

Unfortunately, when substrates **1** derived from aromatic ketones, aliphatic aldehydes, and ketones were used, no cyclodimerisation product was isolated. Probably, this result can be attributed to the low stability of the radical anion intermediates.

In conclusion, the trichlorolanthanoid(cat.)/zinc system can be used for cyclodimerisation of arylidenemalononitriles and arylmethylenecyanoacetates to afford highly functionalised cyclopentene derivatives in both high yields and stereoselectivities. Further studies on the applications of metallic samarium and ytterbium in organic synthesis are now in progress.

Table 1 Cyclodimerisation of arylidenemalononitriles and arylmethylenecyanoacetates promoted by a trichlorolanthanoid(cat.)/zinc system[a]

Entry	Ar	EWG	$LnCl_3$	Yield/%[b]	**5** : other isomers[d]
a	C_6H_5	CN	$YbCl_3$	87 (88[c])	90 : 10 (90 : 10[c])
	C_6H_5	CN	$SmCl_3$	80 (82[c])	86 : 14 (86 : 14[c])
b	4-ClC_6H_4	CN	$YbCl_3$	85	88 : 12
c	3,4-$OCH_2OC_6H_3$	CN	$YbCl_3$	80	84 : 16
d	2-furyl	CN	$YbCl_3$	82	88 : 12
e	3-thienyl	CN	$YbCl_3$	89	88 : 12
	3-thienyl	CN	$SmCl_3$	78	83 : 17
f	C_6H_5	CO_2Et	$YbCl_3$	84 (82[c])	92 : 8 (90 : 10[c])
	C_6H_5	CO_2Et	$SmCl_3$	78 (79[c])	86 : 14 (86 : 14[c])
g	4-ClC_6H_4	CO_2Pr-*i*	$YbCl_3$	85	88 : 12
h	4-$CH_3OC_6H_4$	CO_2Me	$YbCl_3$	84	90 : 10
i	2-furyl	CO_2Et	$YbCl_3$	78	87 : 13
j	3-thienyl	CO_2Et	$YbCl_3$	80	90 : 10

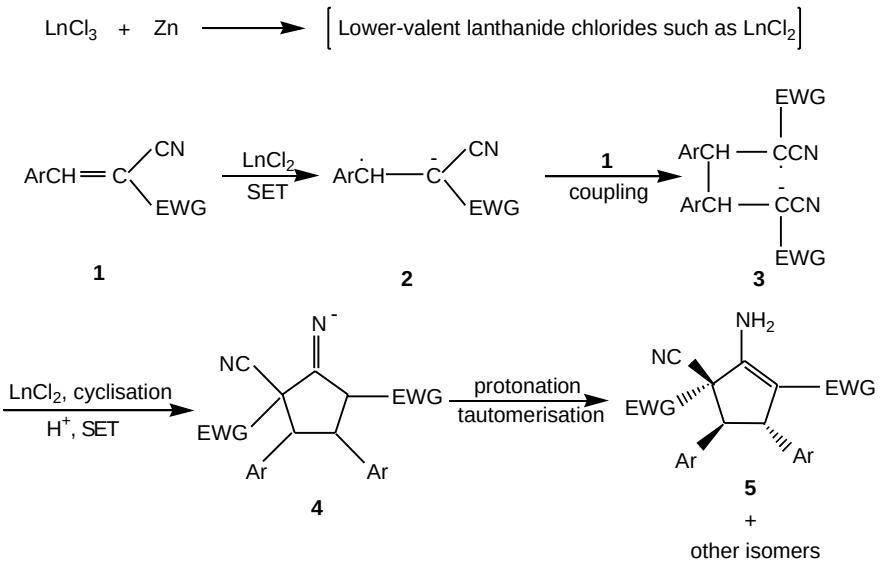
[a]$LnCl_3$ 0.1 mmol, Zn powder 1.5 mmol, THF 4 ml, then substrate **1** 1mmol in 3 ml THF, r.t. [b]Isolated yields based on substrate **1**; [c]$LnCl_3$ 1 mmol was used; [d]Ratios determined by ^1H NMR.

Experimental

Tetrahydrofuran (THF) was distilled from sodium/benzophenone immediately prior to use. All reactions were carried out under a dry nitrogen atmosphere. Arylidenemalononitriles and arylmethylenecyanoacetates were synthesised by the reaction of carbonyl compounds and alkyl cyanoacetates or malononitrile following the usual procedure.[6] Melting points were uncorrected. Infrared spectra were recorded on a Perkin-Elmer 683 spectrometer in KBr with absorptions in cm^{-1}. ^1H NMR spectra were determined on a Bruker AC-400 instrument with $CDCl_3$ used as the solvent. Chemical shifts are expressed in ppm downfield from internal tetramethylsilane. Mass spectra were recorded on a HP 5989B MS spectrometer. Microanalysis was carried out on a Carlo-Erba 1106 instrument.

General procedure: A mixture of anhydrous $LnCl_3$ (0.1 mmol) and Zn powder (1.5 mmol) in THF (4 ml) was stirred at room temperature for 3 h under nitrogen. After the colour of the suspension became green, the arylidenemalononitrile or arylmethylenecyanoacetate 1 (1 mmol) in THF (3 ml) was added and the mixture was stirred at room temperature for 2 h under nitrogen. The products were treated with 0.1 M HCl (5 ml), and then extracted with diethyl ether (3×30 ml). The combined organic extracts were washed with brine and dried over anhydrous $MgSO_4$. After the solvent was evaporated under reduced pressure, the

* Correspondence. E-mail: suweike@zjut.edu.cn



Scheme 2

crude products were purified by preparative TLC on silica gel using ethyl acetate–cyclohexane (1:4) as an eluent. Pure compounds **5** were obtained after fractional crystallisation of the mixture with suitable solvents (a mixture of ether, chloroform and petroleum ether).

2-Amino-1, 3, 3-tricyano-trans-4, 5-diphenylcyclopentene **(5a):** m.p. 129–131°C (lit.[7], 128–130°C); ^{1}H NMR (400 MHz, $CDCl_3$), σ: 3.80 (d, *J* = 9.0 Hz 1H), 4.60 (d, *J* = 9.0 Hz 1H), 5.20 (br s, 2H), 7.15–7.70 (m, 10H); IR (KBr) ν: 3380, 3200, 2210, 1670, 1630, 1505 cm^{-1}.

2-Amino-1, 3, 3-tricyano-trans-4, 5-di(4-chlorophenyl)cyclopentene **(5b):** m.p. 158–161°C (lit.[7], 158–160°C); ^{1}H NMR (400 MHz, $CDCl_3$), σ: 3.74 (d, *J* = 9.5 Hz 1H), 4.50 (d, *J* = 9.5 Hz 1H), 5.32 (br s, 2H), 6.96–7.40 (m, 8H); IR (KBr) ν: 3370, 3200, 2218, 1680, 1630, 1500 cm^{-1}.

2-Amino-1, 3, 3-tricyano-trans-4, 5-di(3, 4-methylenedioxyphenyl) cyclopentene **(5c):** m.p. 166–168°C (lit.[7], 166–168°C); ^{1}H NMR (400 MHz, $CDCl_3$), σ: 4.22 (d, *J* = 9.0 Hz 1H), 4.44 (d, *J* = 9.0 Hz 1H), 5.30 (br s, 2H), 5.98 (s, 4H), 6.66–7.12 (m, 6H); IR (KBr) ν: 3380, 3230, 2210, 1677, 1625, 1510 cm^{-1}.

2-Amino-1, 3, 3-tricyano-trans-4, 5-di(2-furyl)cyclopentene **(5d):** m.p. 126–127°C (lit.[7], 125–127°C); ^{1}H NMR (400 MHz, $CDCl_3$), σ: 4.22 (d, *J* = 9.0 Hz 1H), 4.66 (d, *J* = 9.0 Hz 1H), 5.72 (br s, 2H), 6.19–7.06 (m, 6H); IR (KBr) ν: 3366, 3240, 2210, 1678, 1630, 1510 cm^{-1}.

2-Amino-1, 3, 3-tricyano-trans-4, 5-di(2-thienyl)cyclopentene **(5e):** m.p. 133–135°C; ^{1}H NMR (400 MHz, $CDCl_3$), σ: 3.98 (d, *J* = 9.0 Hz, 1H), 4.62 (d, *J* = 9.0 Hz, 1H), 5.28 (br s, 2H), 6.90–7.45 (m, 6H); IR (KBr) ν: 3362, 3240, 2210, 1680, 1622, 1506 cm^{-1}; MS *m/z* (%) 323 (M$^+$+1, 12), 322 (M$^+$, 36), 321 (15), 289 (26), 162 (26), 161 (37), 149 (100), 85 (23), 84 (30), 83 (21); Anal. calcd for $C_{16}H_{10}N_4S_2$: C 59.63, H 3.11, N, 17.39; found C 59.64, H 3.16, N 17.33.

Diethyl 3, 4-trans-4, 5-trans-2-Amino-3-cyano-4, 5-diphenyl-1-cyclopentene-1, 3-dicarboxylate **(5f):** m.p. 176–177°C (lit.[5], 175–177°C); ^{1}H NMR (400 MHz, $CDCl_3$), σ: 0.86 (t, *J* = 7.2 Hz 3H), 1.31 (t, *J* = 7.2 Hz 3H), 3.90 (d, *J* = 8.8 Hz 1H), 4.00 (dd, *J* = 7.2 Hz 2H), 4.30 (dd, *J* = 7.2 Hz 2H), 4.51 (d, *J* = 8.8 Hz 1H), 5.96 (br s, 2H), 6.90–7.56 (m, 10H); IR (KBr) ν: 3430, 3330, 2255, 1740, 1680, 1630, 830 cm^{-1}.

Diisopropyl 3, 4-trans-4, 5-trans-2-Amino-3-cyano-4, 5-bis(4-chlorophenyl)-1-cyclopentene-1, 3-dicarboxylate **(5g):** m.p. 175–178°C; ^{1}H NMR (400 MHz, $CDCl_3$), σ: 0.67 (d, *J* = 6.0 Hz 3H), 1.00 (d, *J* = 6.0 Hz 3H), 1.23 (d, *J* = 6.0 Hz 3H), 1.30 (d, *J* = 6.0 Hz 3H), 3.80 (d, *J* = 8.0 Hz 1H), 4.29 (d, *J* = 8.0 Hz 1H), 4.76 (m, *J* = 6.0 Hz 1H), 5.15 (m, *J* = 6.0 Hz 1H), 5.96 (br s, 2H), 6.96–7.52 (m, 8H); IR (KBr) ν: 3450, 3343, 3270, 3000, 2250, 1680, 1645, 1580, 1500, 1340, 1100, 820, 770 cm^{-1}; MS *m/z* (%) 502 (M+2, 6), 500 (M$^+$, 7), 457 (15), 413 (16), 370 (20), 352 (14), 43 (100); Anal. calcd for $C_{26}H_{26}Cl_2N_2O_4$: C 62.28, H 5.22, N, 5.58; found: C 62.20, H 5.16, N 5.63.

Dimethyl 3, 4-trans-4, 5-trans-2-Amino-3-cyano-4, 5-bis(4-methoxyphenyl)-1-cyclopentene-1, 3-dicarboxylate **(5h):** m.p. 172–174°C; ^{1}H NMR (400 MHz, $CDCl_3$), σ: 3.40 (s, 3H), 3.60–3.80 (m, 10H), 4.33 (d, *J* = 8.0 Hz 1H), 5.86 (br s, 2H), 6.90–7.30 (m, 8H); IR (KBr) ν: 3440, 3345, 3280, 2970, 2250, 1760, 1690, 1645, 1585, 1520, 1440, 1180, 1030, 830 cm^{-1}; MS *m/z* (%) 437 (M+1, 34), 436 (M$^+$, 100), 403 (34), 376 (60), 371 (65), 344 (52), 328 (48), 316 (33), 218 (38), 174 (25), 160 (52), 121 (55), 59 (35); Anal. calcd for $C_{24}H_{24}N_2O_6$: C 66.04, H 5.54, N, 6.42; found: C 66.16, H 5.70, N 6.29.

Diethyl 3, 4-trans-4, 5-trans-2-Amino-3-cyano-4, 5-di(2-furyl)-1-cyclopentene-1, 3-dicarboxylate **(5i):** m.p. 131–134°C; ^{1}H NMR (400 MHz, $CDCl_3$), σ: 0.80 (t, *J* = 7.0 Hz 3H), 1.26 (t, *J* = 7.0 Hz 3H), 3.70–4.10 (m, 3H), 4.29–4.50 (m, 3H), 5.95 (br s, 2H), 6.17–7.50 (m, 6H); IR (KBr) ν: 3408, 3327, 3260, 3204, 2938, 2875, 2250, 1746, 1678, 1633, 1585, 1465 cm^{-1}; MS *m/z* (%) 384 (M$^+$, 21), 383 (100), 354 (28), 337 (30), 310 (95), 292 (23), 266 (24), 265 (97), 209 (27), 164 (14), 121 (36); Anal. calcd for $C_{20}H_{20}N_2O_6$: C 62.49, H 5.24, N, 7.29; found: C 66.33, H 5.15, N 7.35.

Diethyl 3, 4-trans-4, 5-trans-2-Amino-3-cyano-4, 5-di(3-thienyl)-1-cyclopentene-1, 3-dicarboxylate **(5j):** m.p. 131–134°C; ^{1}H NMR (400 MHz, $CDCl_3$), σ: 1.00 (t, *J* = 7.0 Hz, 3H), 1.30 (t, *J* = 7.0 Hz, 3H), 3.96–4.15 (m, 3H), 4.10–4.66 (m, 3H), 5.96 (br s, 2H), 6.80–7.50 (m, 6H); IR (KBr) ν: 3420, 3326, 3200, 2980, 2938, 2900, 2876, 2248, 1746, 1678, 1630, 1580, 1472 cm^{-1}; MS *m/z* (%) 418 (M+2, 13), 416 (M$^+$, 100), 414 (12), 387 (10), 370 (13), 343 (31), 324 (14), 298 (25), 297 (65), 269 (40), 187 (16), 149 (33), 141 (12), 137 (39), 136 (69), 97 (25), 85 (20), 84 (10); Anal. calcd for $C_{20}H_{20}N_2O_4S_2$: C 57.69, H 4.81, N, 5.77; found: C 57.77, H 4.89, N 5.70.

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