New Methods for the Syntheses of α,β-Unsaturated Ketones, Aldehydes, and Nitriles by the Palladium-Catalyzed Reactions of Allyl β-Oxo Esters, Allyl 1-Alkenyl Carbonates, and Allyl α-Cyano Esters

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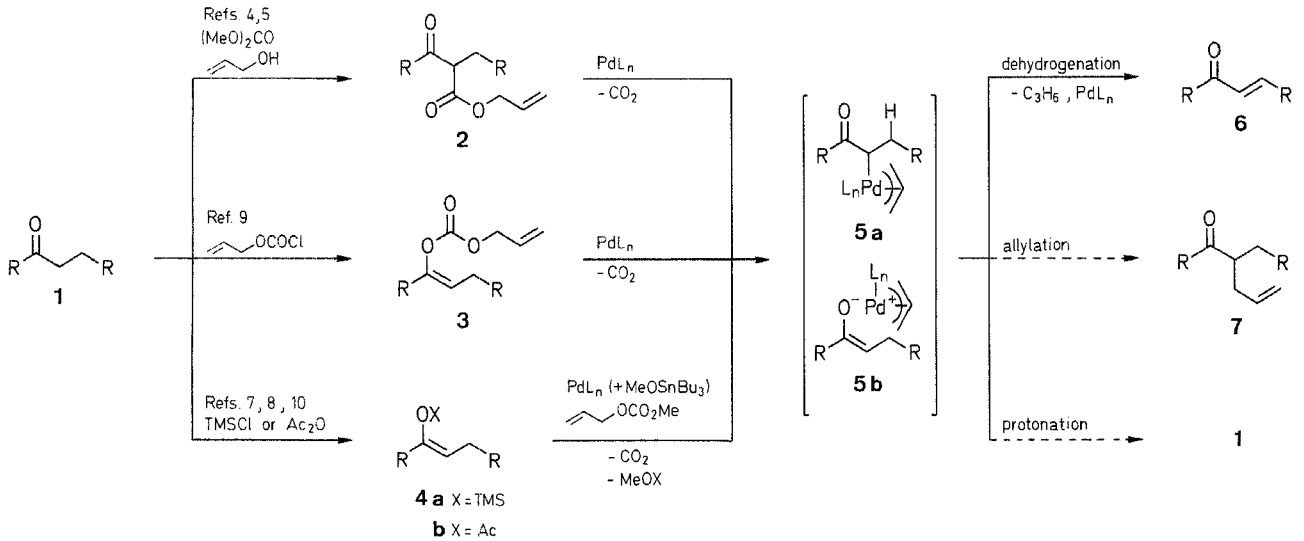
Allyl β-oxo esters, allyl 1-alkenyl carbonates, and allyl α-cyano esters are converted into α,β-unsaturated ketones, aldehydes, and nitriles by palladium-catalyzed intramolecular decarboxylation-dehydrogenation. Palladium-phosphine complexes such as $Pd(OAc)_2$-PPh_3, $Pd(OAc)_2$-dppe, or $Pd_2(dba)_3 \cdot CHCl_3$-PPh_3 are effective catalysts. Yields depend on solvents and on the mole ratio of palladium to phosphine. The optimum Pd/P ratio for each substrate was determined. Use of nitriles as solvents is essential for the dehydrogenation.

The conversion of saturated carbonyl compounds into α,β-unsaturated carbonyl compounds is a synthetically important reaction. There are several established methods which usually involve the introduction of hetero atoms X such as halogen,[1] S,[2] and Se[3] at the α-position, followed by their elimination as HX together with the β-hydrogen. Several years ago, we found that the palladium-catalyzed decarboxylation-allylation reaction of allyl β-oxo esters gives α-allyl ketones **7**.[4] Further, we have discovered that allyl β-oxo esters undergo palladium-catalyzed decarboxylation-dehydrogenation to give α,β-unsaturated ketones under modified reaction conditions, particularly, in terms of solvents and ligands.[5] The decarboxylation-allylation, decarboxylation-dehydrogenation, and deallyloxycarbonylation (decarboxylation-protonation) of allyl β-oxo esters are competitive reactions, so that careful selection of reaction conditions is crucial for the differentiation of these three reactions. The discovery of the decarboxylation-

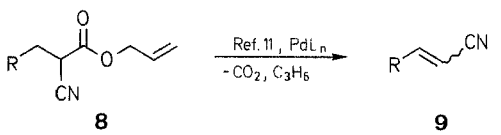
dehydrogenation lead us to establish a new synthetic method for α, β-unsaturated ketones **6** which consists of the formation of (π-allyl)palladium enolate complexes **5a** or **5b**, followed by elimination of the β-hydrogen to liberate propene *via* reductive coupling of the allyl group with the β-hydrogen. At the same time, the Pd(O) catalyst is regenerated. In other words, the (π-allyl)palladium complex acts as a dehydrogenating agent or hydrogen acceptor, which is converted into propene and Pd(O) catalyst. No other dehydrogenating agents are required and hence the reaction can be carried out under mild and clean conditions. The (π-allyl)palladium enolate complexes **5** can be derived from allyl β-oxo esters **2**[4,5] or allyl 1-alkenyl carbonates **3**[9] by intramolecular reactions. Furthermore, we have found that the key intermediates, (π-allyl)palladium enolate complexes **5a** or **5b**, can be prepared by intermolecular reaction of various ketone enolate equivalents such as enol silyl ethers **(4a)**[7,8,10a] and enol acetates **(4b)**[7c,8,10b] with allyl carbonates. The intramolecular method is synthetically useful since only gaseous by-products, namely carbon dioxide and propene, are generated during the reaction. Similarly, allyl α-cyano esters undergo the palladium-catalyzed decarboxylation-dehydrogenation to give α, β-unsaturated nitriles.[11] In a preliminary communication, we have reported that the enone formation proceeds with $Pd(OAc)_2$-dppe catalyst in acetonitrile or dimethylformamide.[5] Later, we have found that also PPh_3 can be used as a ligand, and more importantly, even phosphine-free palladium catalyst in acetonitrile gave better selectivity with regard to α, β-unsaturated ketones.[6] However, turnover of the phosphine-free palladium catalyst is not always satisfactory. Usually, the reaction proceeds with 10 mol % of the catalyst. In the course of further studies, we have found that addition of a small amount of phosphine ligand increases the turnover of the catalyst. As outlined in Scheme **A**, the dehydrogenation, allylation, and protonation reactions proceed via the same intermediates **5**. These competitive reactions can be well controlled by modifying the reaction conditions, particularly with respect to the mole ratio of palladium to phosphine (*P*). Usually, the allylation proceeds in any solvents with a high selectivity when the Pd/P mole ratio is < 0.5. On the other hand, the clean dehydrogenation without contamination of **1** or **7** with palladium-phosphine catalyst is a critical reaction.[6a] We have found that the optimum mole ratio Pd/P depends on the structure of the substrates. For clean enone formation, careful selection of the reaction conditions for each substrate is essential. Here we report details and results of the preparation of α,β-unsaturated ketones, aldehydes, and nitriles by the palladium-catalyzed intramolecular decarboxylation-dehydrogenation of allyl β-oxo esters **2**, allyl 1-alkenyl carbonates **3** (Scheme **A**), and allyl α-cyano esters **8** (Scheme **B**).

Careful selection of reaction conditions is crucial for selective enone formation according to Scheme **A**. One of the factors to be controlled is the selection of solvents. Nitriles seem to be the best ones; dimethylformamide is another good solvent, but it is somewhat inferior to nitriles, giving saturated ketones as by-products. In tetrahydrofuran or dioxan, allylation takes place.[4] Thus, acetonitrile is used most conveniently; however, in some cases, propanenitrile gave better results. As regards the reaction temperature, the reactions should be carried out at 80–100 °C. At room temperature, the reaction proceeds slowly and allylation is the main path even in acetonitrile.

The most crucial factor is the mol ratio of palladium to phosphine ligand (Pd/P). At first, we found that bis(diphenylphosphino)ethane (dppe) is a good ligand,[5] but later we confirmed that triphenylphosphine is satisfactory in most cases. We carefully studied the effect of the mol ratio Pd/*P* in the reaction of allyl 1-methyl-2-oxocyclopentanecarboxylate **(10)** to give 2-methyl-2-cyclopentenone **(11)** which is an important intermediate for the synthesis of certain natural products. A number of methods for the synthesis of the rather simple compound **11** are known,[12] but none of them is satisfactory. We therefore examined the synthesis of **11** from **10** by our method under various conditions in order to find optimum conditions for the desired enone formation. As we have reported previously,



Scheme **A**



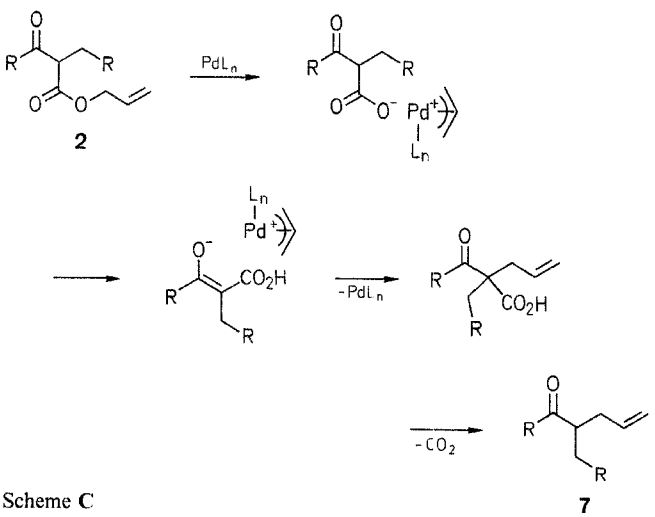
Scheme **B**

the dehydrogenation to give **11** took place selectively in 79% yield, without contamination by 2-allyl-2-methylcyclopentanone or 2-methylcyclopentanone, using the $Pd(OAc)_2$-acetonitrile system which contains the phosphine-free palladium catalyst.[6b] However, reproducibility of the reaction was sometimes unsatisfactory. In such a case, Pd-black deposited during the reaction and conversion was low (20–60%). Use

of the stable zero-valent palladium complex $Pd_2(dba)_3 \cdot CHCl_3$ showed the same tendency. Addition of a small amount of triphenylphosphine increased the conversion. Apparently, the selectivity of enone formation depends strongly on the mol ratio of palladium to phosphine.[6a] Careful experiments to find out the optimum Pd/P mole ratio were carried out using $Pd_2(dba)_3 \cdot CHCl_3$ with different amounts of added triphenylphosphine. The best results were obtained (Table 1) when the mole ratio was 1:0.4–1:0.5. In these cases, neither allylation nor protonation to give **13** or **14** took place. When the mol ratio was 1:0.6, allylation began to take place. The ratio of **13** increases as the Pd/P ratio decreases. When the mole ratio was 1:2, allylation took place predominantly. With freshly distilled acetonitrile, almost no protonation to give **14** took place. Under the optimized conditions, product **11** was isolated in 84% yield (Table 2) by distillation. As the sole by-product, a small amount of 2-methylenecyclopentanone **(12)** was formed.

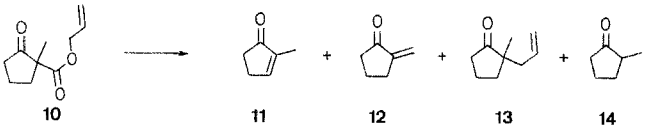
The preparation of α,β-unsaturated carbonyl compounds from allyl β-oxo esters and allyl 1-alkenyl carbonates was performed with several substrates (Table 2). The most suitable Pd/P mole ratio depends slightly on the structure of the substrates. For example, the effective Pd/P mole ratio for the conversion **15** → **16** was found to be 1:1. In all cases, the dehydrogenation proceeds with good conversion (> 98%, GLC analysis) and with good selectivity.

From a mechanistic point of view, both allyl β-oxo esters **2** and allyl 1-alkenyl carbonates **3** give the (π-allyl)palladium enolate complex **5** as the common intermediate upon treatment with zero-valent palladium complex. From a synthetic viewpoint, the two substrates **2** and **3** for enone formation should be used complementarily. α-Alkyl-α,β-unsaturated ketones such as **11**, **16**, or **24** can be prepared *via* allyl β-oxo esters, since introduction of an α-alkyl group into a β-oxo ester is a well-established method.[13] On the other hand, it is rather difficult to convert allyl β-oxo esters bearing an active H-atom at the α-position (C-2) into α, β-unsaturated ketones due to intramolecular proton transfer, followed by allylation and thermal decarboxylation to afford **7** as a major product, as shown in Scheme **C**. For example, the reaction of allyl 2-oxocyclopentanecarboxylate produced 2-allylcyclopentanone and cyclopentanone as major products. In this case, allyl 1-alkenyl carbonates **3** are suitable substrates for enone formation since there is no active hydrogen. 2-Cyclopentenone **(20)** was obtained in high yield from allyl 1-cyclopentenyl carbonate **(19)**. Also α, β-unsaturated aldehydes can be prepared in good yields from allyl 1-alkenyl carbonates.



Scheme C

Table 1. Selectivity of Enone Formation from Allyl 1-Methyl-2-oxocyclopentanecarboxylate **(10)**[a]



10 **11** **12** **13** **14**

mole Ratio Pd/P	Reaction Time (h)	Conversion (%)	Ratio of Products **11**:**12**:**13**:**14**
1/0	1	72	96: 3: 1: 0
1/0.2	1	87	96: 3: 1: 0
1/0.3	1	89	94: 3: 2: 1
1/0.4	1	91	97: 3: 0: 0
1/0.5	1	94	98: 2: 0: 0
1/0.6	1	58	84: 2:14: 0
1/0.7	1	33	62: 7:31: 0
1/0.8	1	52	46: 0:54: 0
1/1	1	98	30: 0:70: 0
1/2	1	98	2: 0:98: 0

[a] Reactions were carried out using **10** (1 mmol) and $Pd_2(dba)_3 \cdot CHCl_3$ (0.025 mmol) in MeCN (5 mL) under argon. Conversion and ratio of **11**:**12**:**13**:**14** were determined by GLC analyses.

The decarboxylation of the salts of β-oxo carboxylic acids proceeds smoothly, because the carbanion generated by the decarboxylation is stabilized by a ketonic group. Thus, a similar decarboxylation is expected for allyl carboxylates which have other electron-withdrawing groups at C-2. Based on this expectation, we examined the palladium-catalyzed decarboxylation-dehydrogenation of allyl esters of substituted malonic, cyanoacetic, and nitroacetic acids. The decarboxylation-dehydrogenation of allyl α-cyano esters proceeded smoothly with $Pd_2(dba)_3 \cdot CHCl_3$-PPh_3 (2:1) catalyst in propanenitrile at 100°C (Table 3). In boiling acetonitrile, the reaction was not complete even after 10 h. A mixture of *E* and *Z* forms was obtained from **34** and **37**. The isomers *(E)*-**38** and *(Z)*-**38** were isolated by preparation GLC and identified by comparison of their ^{1}H-NMR spectra with the reported spectra.[14] Under the reaction conditions used, the expected allylation did not take place with the allyl α-cyano ester **37** even though it has an active H-atom at C-2.[15] As a sole by-product, hexanenitrile **(39)** was detected in minor amounts. Contrary to our expectation, the selectivity for the decarboxylation-dehydrogenation is highly dependent on electron-withdrawing groups. With allyl esters of substituted malonic and nitroacetic acids, protonation took place predominantly and α,β-unsaturated compounds were obtained in low yields (0–20%).

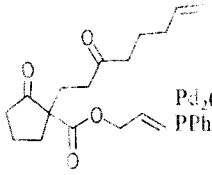
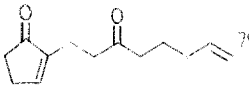
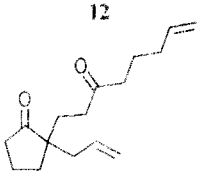
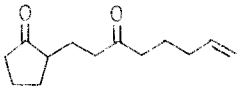
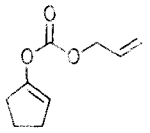
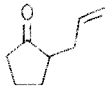
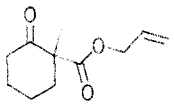
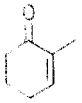
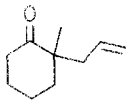
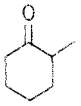
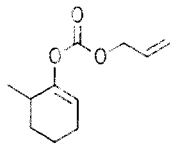
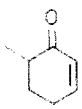
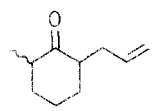
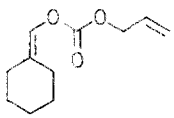
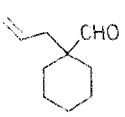
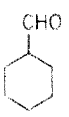
GLC analyses were performed on a Shimadzu Model GC-4C(PT) gas chromatograph (column: 3 m × 3 mm ∅; 10% silicone SE-30 on 80/100 Celite 545; carrier gas: He): IR spectra were obtained on a JASCO Model IRA-2 spectrometer. ^{1}H-NMR spectra were recorded on a JEOL Model FX-90Q Fourier transform spectrometer at 90 MHz or on a Hitachi Model R-24A at 60 MHz. ^{13}C-NMR spectra were recorded on a JEOL Model FX-90Q Fourier-transform spectrometer at 22.5 MHz.

Acetonitrile and propanenitrile were dried with P_2O_5 and distilled under argon before use. The catalysts $Pd_2(dba)_3 \cdot CHCl_3$[16] and $Pd(OAc)_2$[17] were prepared by the published procedure. Triphenylphosphine and bis(diphenylphosphino)ethane were purchased and recrystallized from EtOH. Authentic α-allyl ketones **13**, **17**, **21**, **25**, **29**, and aldehyde **32** for GLC analysis were prepared *via* palladium-catallyzed allylation of allyl β-oxo esters or enol silyl ethers.[4a,9a] Authentic 2-methylenecyclopentanone **(12)** was prepared by the palladium-cata-

lyzed decarboxylation-deacetoxylation of allyl 1-acetoxymethyl-2-oxocyclopentanecarboxylate.[18] Allyl 1-methyl-2-oxocyclopentanecarboxylate (**10**) was prepared by the reported procedure.[6b]

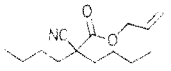
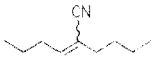
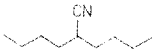
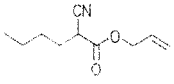
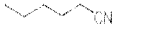
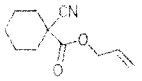
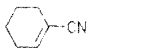
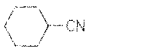
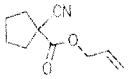
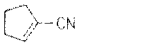
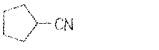
Allyl 2-Oxo-1-(3-oxo-7-octenyl)cyclopentanecarboxylate (15):
A solution of 1,7-octadien-3-one [12.4 g, 0.1 mol; prepared by Pd-catalyzed telomerization of butadiene and acetic acid,[19b] followed by hydrolysis with K_2CO_3 (2 equiv) in MeOH, and Ru-catalyzed oxidation of the resultant 1,7-octadien-3-ol with allyl methyl carbonate[19a]] in dry acetone (15 mL) is added dropwise to a stirred suspension of K_2CO_3 (34.5 g, 0.25 mol) and allyl 2-oxocyclopentanecarboxylate (12.6 g, 0.75 mol; prepared by Dieckmann condensation of diallyl adipate[9b]) in dry acetone (15 mL). Stirring is continued for 2 h. When the reaction is complete (TLC analysis), the mixture is cooled to room temperature and filtered through celite. The filtrate is neutralized with ice-cold 1 normal HCl and extracted with Et_2O (3 × 100 mL). The

Table 2. Synthesis of α,β-Unsaturated Ketones and Aldehydes

Substrate	Catalyst Pd:P (ratio)	Solvent	Product	Yield[a] (%)	Conversion[b] (%)	By-products	Selectivity[b]
10[c]	$Pd_2(dba)_3 \cdot CHCl_3$/ PPh_3 (2:1)	MeCN	**11**	84	98	**12**	**11**:**12** = 96:4
 **15**	$Pd_2(dba)_3 \cdot CHCl_3$/ PPh_3 (1:1)	MeCN	 **16**	79	98	 **17**  **18**	**16**:**17**:**18** = 89:4:7
15	$Pd_2(dba)_3 \cdot CHCl_3$/ PPh_3 (2:1)	MeCN	**16**		98		**16**:**17**:**18** = 66:21:13
15	$Pd(OAc)_2$/ PPh_3 (1:1)	MeCN	**16**		99		**16**:**17**:**18** = 86:1:13
 **19**	$Pd(OAc)_2$/ PPh_3 (5:2)	MeCN	 **20**	71	98	 **21**  **22**	**20**:**21**:**22** = 96:0.5:3.5
19	$Pd(OAc)_2$/ PPh_3 (1:1)	MeCN	**20**		98		**19**:**20**:**21** = 92:5:3
19	$Pd(OAc)_2$/ PPh_3 (1:0.4)	EtCN	**20**		99		**19**:**20**:**21** = 96:1:3
 **23**	$Pd(OAc)_2$/ dppe (2:1)	MeCN	 **24**	72	99	 **25**  **26**	**24**:**25**:**26** = 88:4:8
23	$Pd(OAc)_2$/ PPh_3 (1:1)	MeCN	**24**		99		**24**:**25**:**26** = 85:7:8
23	$Pd(OAc)_2$/ dppe (2:1)	MeCN	**24**		98		**24**:**25**:**26** = 91:5:4
 **27**	$Pd(OAc)_2$/ PPh_3 (5:4)	MeCN	 **28**	77	99	 **29**	**28**:**29**:**26** = 93:1:6
27	$Pd(OAc)_2$/ PPh_3 (1:1)	MeCN	**28**		99		**28**:**29**:**26** = 90:3:7
27	$Pd(OAc)_2$/ PPh_3 (2:1)	MeCN	**28**		100		**28**:**29**:**26** = 93:0:7
 **30**	$Pd(OAc)_2$/ PPh_3 (1:1)	MeCN	 **31**	82	99	 **32**  **33**	**31**:**32**:**33** = 95:4:1
30	$Pd(OAc)_2$/ PPh_3 (1:1)	MeCN	**31**		100		**31**:**32**:**33** = 89:8:3
30	$Pd(OAc)_2$/ PPh_3 (2:1)	MeCN	**31**		100		**31**:**32**:**33** = 90:9:1

[a] Yield of distilled product. Procedure given in the experimental part. [b] Determined by GLC analysis.

Table 3. Preparation of α,β-Unsaturated Nitriles[a]

Substrate	Solvent	Product	Yield[b] (%)	Conversion[c] (%)	By-product	Selectivity[c]
 **34**	EtCN	 **35**	78	98	 **36**	**35** : **36** = 96 : 4 (*E*)-**35**: (*Z*-**35**) = 8 : 1
34	MeCN	35		38		**35** : **36** = 3 : 4
 **37**	EtCN	 **38**	65	96	 **39**	**38** : **39** = 99 : 1 (*E*)-**38**: (*Z*)-**38** = 5 : 3
 **40**	EtCN	 **41**	81	100	 **42**	**41** : **42** = 92 : 8
 **43**	EtCN	 **44**	78	98	 **45**	**44** : **45** = 99 : 1

[a] Procedures are given in the experimental part.
[b] Yield of pure product isolated by column chromatography on silica gel.
[c] Determined by GLC analysis.

combined extract is washed with saturated NaCl solution (50 mL), dried ($MgSO_4$), and evaporated. The residue is purified by column chromatography on silica gel using Et_2O/hexane (1 : 7) as eluent; yield of **15**: 19.2 g (88%); oil.

$C_{17}H_{24}O_4$ (292.4) calc. C 70.56 H 8.36 found 70.47 8.48

IR (neat): ν = 2962, 1780, 1755, 1645, 1210 cm^{-1}.

^{1}H-NMR ($CDCl_3$/TMS): δ = 1.64–2.14 (m, 10 H); 2.32–2.48 (m, 6 H); 4.60 (d, J = 5.5 Hz, 2 H); 4.89–5.39 (m, 4 H); 5.68–6.02 (m, 2 H).

Allyl 1-Cyclopentenyl Carbonate (19):

A solution of cyclopentanone (25 g, 0.3 mol) in dry THF (30 mL) is added to a stirred suspension of *t*-BuOK (50.4 g, 0.45 mol) in dry THF (500 mL) at 20–30 °C under N_2. Stirring is continued for 2 h, the resultant yellow solution is added dropwise to a solution of allyl chloroformate (53.9 g, 0.45 mol) in dry THF (50 mL) at 0 °C, and the mixture is stirred for 5 h. When the reaction is complete (TLC analysis), the mixture was diluted with Et_2O (1000 mL), washed with saturated NaCl solution (100 mL), and dried ($MgSO_4$). Product **19** is isolated by distillation; yield: 21.3 g (41%); b.p. 58 °C/2 Torr.

MS: m/e = 67 ($C_5H_7^+$).

IR (neat): ν = 2950, 1760, 1655 cm^{-1}.

^{1}H-NMR (CCl_4/TMS): δ = 1.70–3.00 (m, 6 H); 4.52 (d, J = 6 Hz, 2 H); 5.00–5.50 (m, 3 H); 5.50–6.30 (m, 1 H).

Allyl Cyclohexylidenemethyl Carbonate (3):

Prepared from cyclohexanecarboxaldehyde (22.44 g, 0.2 mol) and allyl chloroformate (36.16 g, 0.3 mol) by the procedure described for **19**; yield of **30**: 32 g (73%); b.p. 83 °C/2 Torr.

MS: m/e = 196 (M^+).

IR (neat): ν = 2950, 1760, 1690, 1650 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.30–2.90 (m, 10 H); 4.52 (d, J = 6 Hz, 2 H); 5.00–5.50 (m, 2 H); 5.50–6.30 (m, 1 H); 6.55 (br s, 1 H).

Allyl 1-Methyl-2-oxocyclohexanecarboxylate (23):

Allyl 2-Oxocyclohexanecarboxylate: A solution of methyl 2-oxocyclohexanecarboxylate (80 g, 0.51 mol, prepared from cyclohexanone and dimethyl carbonate,[20] and sodium (15 mg, 0.23 mmol) in allyl alcohol (500 mL) is refluxed for 24 h with continuous removal of methanol using a Claisen head. After the reaction is complete (GLC analysis), the mixture is diluted with CH_2Cl_2 (500 mL), washed with saturated NH_4Cl solution (50 mL) and saturated NaCl solution (50 mL), and dried ($MgSO_4$). Removal of the solvent, followed by distillation of the residue (Kugelrohr) affords the allyl ester which is used in the next step without further purification; yield: 67 g (72%); b.p. 140 °C (bath)/ 0.1 Torr.

Allyl 1-Methyl-2-oxocyclohexanecarboxylate (**23**): A mixture of the crude allyl 2-oxocyclohexanecarboxylate (69 g, 0.38 mol), K_2CO_3 (103 g, 0.74 mol), and iodomethane (105 g, 0.74 mol) in dry acetone (500 mL) is refluxed for 5 h under N_2. After the reaction is complete (TLC analysis), the mixture is filtered through celite. The filtrate is diluted with Et_2O (1000 mL), washed with saturated NaCl solution (100 mL), and dried ($MgSO_4$). Product **23** is isolated by distillation; yield: 57.7 g (77%); b.p. 80 °C/0.1 Torr.

$C_{11}H_{16}O_3$ (196.2) calc. C 67.32 H 8.22 found 67.56 8.27

IR (neat): ν = 2930, 1735, 1715, 1645 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.20 (s, 3 H); 1.40–2.00 (m, 6 H); 2.20–2.60 (m, 2 H); 4.45 (d, J = 6 Hz, 2 H); 4.50–5.40 (m, 2 H); 5.50–6.00 (m, 1 H).

Allyl 6-Methyl-1-cyclohexenyl Carbonate (27):

A solution of potassium bis(trimethylsilyl)amide in THF is prepared from KH (16.3 g, 0.4 mol) and hexamethyldisilazane (48.8 g, 0.28 mol) in THF (250 mL) by the published procedure, under N_2.[21] The THF solution of the base is cooled to –78 °C and a solution of 2-methylcyclohexanone (22.4 g, 0.2 mol) in dry THF (30 mL) is added dropwise over 1 h with stirring at –78 °C. The resultant solution is stirred for 2 h at –78 °C. Then, a solution of allyl chloroformate (33.6 g, 0.28 mol) in dry THF (20 mL) is added in one portion at –78 °C. The mixture was gradually warmed to 25 °C and stirred for 3 h. After the reaction is complete (TLC analysis), the mixture is diluted with Et_2O (500 mL), washed with saturated NaCl solution (3 × 100 mL), and dried ($MgSO_4$). Product **27** is isolated by distillation; yield: 29 g (74%); b.p. 70 °C/2 Torr.

MS: m/e = 196 (M^+).

IR (neat): ν = 2950, 1760, 1685 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 0.95 (d, J = 6 Hz, 3 H); 1.15–3.00 (m, 7 H); 4.52 (d, J = 6 Hz, 2 H); 5.00–5.50 (m, 3 H); 5.50–6.20 (m, 1 H).

Preparation of α,β-Unsaturated Ketones and Aldehydes:

2-Methyl-2-cyclopentenone (**11**); *Typical Procedure:* In a 50 mL two-necked flask, equipped with a dropping funnel and a reflux condenser are placed PPh_3 (65 mg, 0.25 mmol) and $Pd_2(dba)_3 \cdot CHCl_3$ (259 mg, 0.25 mmol, Pd/*P* ratio 2 : 1) and the apparatus is flushed with argon. Acetonitrile (10 mL) is added and the mixture is stirred at 20–30 °C for

10 min. The reaction flask is then immersed in a pre-heated oil bath (100 °C) and a solution of allyl 1-methyl-2-oxocyclopentanecarboxylate **10**; 9.1 g, 50 mmol) in MeCN (10 mL) is added dropwise over 10 min with stirring. The resultant solution is refluxed for 1.5 h. After the reaction is complete (TLC and/or GLC analyses), the mixture is cooled to room temperature and filtered through Florisil®. Fractional distillation of the filtrate affords product **11**; yield: 4.63 g (84%); b.p. 87 °C/70 Torr (Lit.[6b] b.p. 74 °C/44 Torr).

2-(3-Oxo-7-octenyl)-2-cyclopentenone **(16)**: A solution of allyl 2-oxo-1-(3-oxo-7-octenyl)-cyclopentanone (**15**; 11.7 g, 40 mmol), $Pd_2(dba)_3 \cdot CHCl_3$ (518 g, 0.5 mmol), and PPh_3 (262 mg, 1 mmol) in MeCN (35 mL) is refluxed for 2 h. Product **16** is isolated by column chromatography on silica gel Et_2O/hexane 1:8); yield: 6.5 g (79%); oil.

Exact Mass: calc. for $C_{13}H_{18}O_2$: 206.2844, found: 206.1321.

IR (neat): ν = 2900, 1700, 1635, 1435, 1000, 910 cm^{-1}.

^{1}H-NMR ($CDCl_3$): δ = 1.58–1.82 (m, 2H); 1.94–2.08 (m, 2H); 2.32–2.62 (m, 10H); 4.89–5.07 (m, 2H); 5.54–5.91 (m, 1H); 7.28–7.35 (br s, 1H).

2-Cyclopentenone **(20)**: A solution of allyl 1-cyclopentenyl carbonate (**19**; 18 g, 0.1 mol), $Pd(OAc)_2$ (440 mg, 2 mmol), and PPh_3 (208 mg, 0.8 mmol) in MeCN (60 mL) is refluxed for 1.5 h. Product **20** is isolated by filtration through Florisil® and distillation; yield: 6.3 g (71%); b.p. 65 °C/20 Torr (Lit.[22] b.p. 43.5 °C/11 Torr).

IR (neat): ν = 2920, 2200, 1720, 1585, 1180, 915, 750 cm^{-1}.

^{1}H-NMR ($CDCl_3$): δ = 2.31–2.41 (m, 2H); 2.66–2.76 (m, 2H); 6.21 (dt, J = 5.6, 2.2 Hz, 1H); 7.73 (dt, J = 5.6, 2.6 Hz, 1H).

2-Methyl-2-cyclohexenone **(24)**: A solution of allyl 1-methyl-2-oxocyclohexanecarboxylate (**23**; 19.8 g, 0.1 mol), $Pd(OAc)_2$ (440 mg, 2 mmol), and dppe (406 mg, 1 mmol) in MeCN (50 mL) is refluxed for 4 h. Product **24** is isolated by distillation; yield: 7.9 g (72%); b.p. 73 °C/15 Torr (Lit.[23] b.p. 83–85.5 °C/35 Torr).

IR (neat): ν = 2920, 1675 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.67 (d, J = 2 Hz, 3H); 1.80–2.60 (m, 6H); 6.50–6.80 (m, 1H).

6-Methyl-2-cyclohexenone **(28)**: A solution of allyl 6-methyl-1-cyclohexenyl carbonate (**27**; 19.6 g, 0.1 mol), $Pd(OAc)_2$ (270 mg, 1.25 mmol), and PPh_3 (304 mg, 1.16 mmol) in MeCN (60 mL) is refluxed for 2 h. Product **28** is isolated by distillation; yield: 8.5 g (77%); b.p. 80 °C/20 Torr (Lit.[24] b.p. 75 °C/18 Torr).

IR (neat): ν = 2920, 1675 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.07 (d, J = 6 Hz, 3H); 1.50–2.10 (m, 5H); 5.84 (dt, J = 10, 2 Hz, 1H); 6.79 (dt, J = 10, 4 Hz, 1H).

Cyclohexene-1-carboxaldehyde **(31)**: A solution of allyl cyclohexylidenemethyl carbonate (**30**; 19.6 g, 0.1 mol), $Pd(OAc)_2$ (220 mg, 1 mmol), and PPh_3 (262 mg, 1 mmol) in MeCN (60 mL) is refluxed for 1.5 h, product **31** is isolated by distillation; yield: 8.8 g (82%); b.p. 63–65 °C/14 Torr (Lit.[25] b.p. 69–71 °C/18 Torr).

IR (neat): ν = 2920, 1680, 1640, 1180 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.50–2.50 (m, 8H); 6.50–6.80 (br s, 1H); 9.36 (s, 1H).

Allyl 2-Cyanohexanoate (37):

A suspension of K_2CO_3 (2.76 g, 20 mmol), allyl cyanoacetate (2.50 g, 20 mmol), and 1-iodobutane (3.68 g, 20 mmol) in dry acetone (100 mL) is refluxed for 4 h under N_2. The reaction is monitored by GLC. As soon as dialkylated product is detected, the mixture is filtered through Celite to remove inorganic salts. The filtrate is diluted with CH_2Cl_2 (150 mL), washed with saturated NH_4Cl solution (20 mL) and with saturated NaCl solution (20 mL), dried ($MgSO_4$), and purified by column chromatography on silica gel; yield: 3.0 g (83%); oil.

$C_{10}H_{15}NO_2$	calc.	C 66.27	H 8.34	N 7.73
(181.2)	found	66.42	8.36	7.87

IR (neat): ν = 2950, 2850, 2240, 1745, 1645, 1450, 990, 935 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 0.70–1.10 (m, 3H); 1.10–1.60 (m, 4H); 1.60–2.10 (m, 2H); 3.30 (t, J = 6.5 Hz, 1H); 4.42 (d, J = 5 Hz, 2H); 4.95–5.40 (m, 2H; 5.45–6.15 (m, 1H).

Allyl 2-Butyl-2-cyanohexanoate (34):

This compound is similarly prepared from allyl cyanoacetate (6.26 g, 50 mmol), 1-iodobutane (27.6 g, 150 mmol), and K_2CO_3 (34.55 g, 250 mmol), and isolated by distillation; yield: 12.7 g (86%); b.p. 90–91 °C/1 Torr.

$C_{14}H_{23}NO_2$	calc.	C 70.85	H 9.77	N 5.90
(237.3)	found	70.86	9.71	5.81

IR (neat): ν = 2930, 2850, 2230, 1740, 1640, 1450, 990, 935 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 0.65–1.05 (m, 6H); 1.05–1.55 (m, 8H); 1.55–2.20 (m, 4H); 4.40–4.80 (m, 2H); 4.85–5.45 (m, 2H); 5.45–6.15 (m, 1H).

Allyl 1-Cyanocyclohexanecarboxylate (40):

This compound is similarly prepared from allyl cyanoacetate (6.26 g, 50 mmol), 1,5-dibromopentane (11.5 g, 50 mmol), and K_2CO_3 (20.74 g, 150 mmol), and isolated by distillation; yield: 7.0 g, 73%): b.p. 84–85 °C/1 Torr.

$C_{11}H_{15}NO_2$	calc.	C 68.37	H 7.82	N 7.25
(193.2)	found	68.47	7.83	7.55

IR (neat): ν = 2950, 2870, 2240, 1740, 1645, 1440, 995, 935 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.00–2.35 (m, 10H); 4.40–4.65 (m, 2H); 4.95–5.45 (m, 2H); 5.45–6.12 (m, 1H).

Allyl 1-Cyanocyclopentanecarboxylate (43):

This compound is similarly prepared from allyl cyanoacetate (6.26 g, 50 mmol), 1,4-dibromobutane (10.77 g, 50 mmol), and K_2CO_3 (20.74 g, 150 mmol), and isolated by distillation; yield: 7.6 g (85%); b.p. 80–82 °C/1 Torr.

$C_{10}H_{13}NO_2$	calc.	C 67.02	H 7.31	N 7.82
(179.2)	found	67.05	7.31	8.00

IR (neat): ν = 2950, 2870, 2240, 1740, 1645, 1440, 995, 935 cm^{-1}.

^{1}H-NMR (CCl_4): δ = 1.60–2.05 (m, 4H); 2.05–2.45 (m, 4H); 4.45–4.75 (m, 2H); 4.95–5.40 (m, 2H); 5.40–6.25 (m, 1H).

Preparation of α,β-Unsaturated Nitriles (2-Alkenenitriles):

(Z)- and (E)-5-Cyano-4-nonene [**(Z)-35** + **(E)-35**]; *Typical Procedure*: In a 30 mL two-necked flask fitted with a reflux condenser are placed $Pd_2(dba)_3 \cdot CHCl_3$ (13 mg, 0.0125 mmol), and PPh_3 (5.6 mg, 0.025 mmol) and the flask is filled with argon. Propanenitrile (2 mL) is added to the flask and the catalyst is dissolved. To this solution, a solution of allyl 2-butyl-2-cyanohexanoate **34**; 237 mg, 1 mmol) in propanenitrile (3 mL) is added and the mixture is refluxed for 1 h under argon. The mixture is then analyzed by GLC to determine the selectivities [**35**:**36** = 96:4 and (*E*)-**35**: (*Z*)-**35** = 8:1], and the product is isolated as a mixture of (*Z*)-**35** and (*E*)-**35** by column chromatography on silica gel (ether/hexane 1:10); yield: 118 mg (78%). The analytically pure isomers are isolated by preparative GLC.

(Z)-5-Cyano-4-nonene [**(Z)-35**]:[8]

IR (neat): ν = 2940, 2860, 2240, 1460, 910, 740 cm^{-1}.

^{1}H-NMR ($CDCl_3$): δ = 0.92 (t, J = 7.7 Hz, 3H); 0.94 (t, J = 7.7 Hz, 3H); 1.28–1.80 (m, 6H); 2.21–2.37 (m, 4H); 6.13 (t, J = 7.5 Hz, 1H).

^{13}C-NMR ($CDCl_3$): δ = 13.5, 13.6, 21.7, 21.9, 30.2, 33.4, 33.9, 115.0, 117.8, 147.3.

(E)-5-Cyano-4-nonene [**(E)-35**]:[8]

IR (neat): ν = 2950, 2920, 2860, 2210, 1630, 1460, 910, 730 cm^{-1}.

^{1}H-NMR ($CDCl_3$): δ = 0.93 (t, J = 6.8, 6H); 1.23–1.65 (m, 6H); 2.03–2.28 (m, 4H); 6.33 (t, J = 7.6 Hz, 1H).

^{13}C-NMR ($CDCl_3$): δ = 13.7, 21.8, 22.1, 28.3, 30.2, 30.4, 115.2, 120.2, 147.8.

(Z)-and (E)-2-Hexenenitrile [**(Z)-38** + **(E)-38**]: A solution of allyl 2-cyanohexanoate (**37**; 181 mg, 1 mmol), $Pd_2(dba)_3 \cdot CHCl_3$ (26 mg, 0.025 mmol), and PPh_3 (5.6 mg, 0.025 mmol) in propanenitrile (5 mL) is refluxed for 2 h and then worked up as described above; yield: 62 mg (65%).

(E)-2-Hexenenitrile [**(E)-38**]:

IR (neat): ν = 2960, 2870, 2220, 1620, 1460, 915, 730 cm^{-1}.

^{1}H-NMR ($CDCl_3$): δ = 0.96 (t, J = 6.8 Hz, 3H); 1.28–1.75 (m, 2H); 2.20–2.56 (m, 2H); 5.30 (dt, J = 10.8, 1.1 Hz, 1H); 6.46 (dt, J = 10.8, 7.6 Hz, 1H).

(Z)-2-Hexenenitrile [**(Z)-38**]:

IR (neat): ν = 3020, 2960, 2860, 2220, 1630, 960, 760 cm^{-1}.

^{1}H-NMR ($CDCl_3$): δ = 0.94 (t, J = 7 Hz, 3H); 1.37–1.58 (m, 2H); 2.10–2.33 (m, 2H); 5.32 (dt, J = 16.3, 1.5 Hz, 1H); 6.72 (dt, J = 16.3, 6.9 Hz, 1H).

1-Cyanocyclohexene **(14)**: A solution of allyl 1-cyanocyclohexanecarboxylate (**40**; 193 mg, 1 mmol), $Pd_2(dba)_3 \cdot CHCl_3$ (52 mg, 0.05 mmol),

and PPh_3 (5.6 mg, 0.025 mmol) in propanenitrile (5 mL) is refluxed for 1 h and then worked up as described above; yield: 87 mg (81%).

IR (neat): ν = 2930, 2850, 2200, 1640, 1440, 920 cm^{-1}.

^1H-NMR ($CDCl_3$): δ = 1.46–1.86 (m, 4H); 2.36 (br s, 4H); 6.44–6.72 (m, 1H).

1-Cyanocyclopentene (**44**): A solution of allyl 1-cyanocyclopentanecarboxylate (**43**; 179 mg, 1 mmol), $Pd_2(dba)_3 \cdot CHCl_3$ (52 mg, 0.05 mmol), and PPh_3 (5.6 mg, 0.025 mmol) in propanenitrile (5 mL) is refluxed for 1.5 h and then worked up as described above; yield: 72 mg (77%).

IR (neat): ν = 2940, 2200, 1610, 1440 cm^{-1}.

^1H-NMR ($CDCl_3$): δ = 1.60–2.24 (m, 2H); 2.36–2.88 (m, 4H); 6.45–6.80 (m, 1H).

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(1) Stotter, P.L., Hill, K.A. *J. Org. Chem.* **1973**, *38*, 2576.
(2) Trost, B.M., Salzmann, T.N., Hiroi, K. *J. Am. Chem. Soc.* **1976**, *98*, 4887.
(3) a) Reich, H.J., Reich, I.L., Renga, J.M. *J. Am. Chem. Soc.* **1973**, *95*, 5813.
b) Sharpless, K.B., Lauer, R.F., Teranishi, A.Y. *J. Am. Chem. Soc.* **1973**, *95*, 6137.
(4) a) Shimizu, I., Yamada, T., Tsuji, J. *Tetrahedron Lett.* **1980**, *21*, 3199.
b) Tsuda, T., Chujo, Y., Nishi, S., Tawara, K., Saegusa, T. *J. Am. Chem. Soc.* **1980**, *102*, 6381.
(5) Shimizu, I., Tsuji, J. *J. Am. Chem. Soc.* **1982**, *104*, 5844.
(6) a) Tsuji, J., Minami, I., Shimizu, I., Kataoka, H. *Chem. Lett.* **1984**, 1133.
b) Tsuji, J., Nissar, M., Shimizu, I., Minami, I. *Synthesis* **1984**, 1009.
(7) a) Tsuji, J., Minami, I., Shimizu, I. *Tetrahedron Lett.* **1983**, *24*, 5635.
b) Tsuji, J., Takahashi, K., Minami, I., Shimizu, I. *Tetrahedron Lett.* **1984**, *25*, 4783.
c) Minami, I., Takahashi, K., Shimizu, I., Kimura, T., Tsuji, J. *Tetrahedron* **1986**, *42*, 2971.
(8) Tsuji, J., Minami, I., Shimizu, I. *Tetrahedron Lett.* **1983**, *24*, 5639.
(9) a) Tsuji, J., Minami, I., Shimizu, I. *Tetrahedron Lett.* **1983**, *24*, 1793.
b) Shimizu, I., Minami, I., Tsuji, J. *Tetrahedron Lett.* **1983**, *24*, 1797.
(10) a) Tsuji, J., Minami, I., Shimizu, I. *Chem. Lett.* **1983**, 1325.
b) Tsuji, J., Minami, I., Shimizu, I. *Tetrahedron Lett.* **1983**, *24*, 4713.
(11) Minami, I., Yuhara, M., Tsuji, J. *J. Chem. Soc. Chem. Commun.* **1986**, 118.
(12) A good summary of the preparative methods reported before 1980 is given:
Funk, R.L., Vollhadt, K.P.C. *Synthesis* **1980**, 118.
Recent reports:
Disanayaka, *B.W., Weedon, A.C. Synthesis* **1983**, 952.
Rautenstrauch, V. *J. Org. Chem.* **1984**, *49*, 591.
(13) For reviews, see: McMurry, J. *Org. React.* **1976**, *24*, 187.
Krapcho, A.P. *Synthesis* **1982**, 805, 893.
(14) Breuer, E., Bannet, D.M. *Tetrahedron* **1978**, *34*, 997.
(15) We confirmed that the palladium-catalyzed decarboxylation-allylation of allyl α-cyano carboxylates proceeds in dioxane:
Tsuji, J., Yamada, T., Minami, I., Yuhara, M. Nisar, M., Shimizu, I. *J. Org. Chem.* **1987**, *52*, 2988.
(16) Ukai, T., Kawazura, H., Ishii, Y., Bonnet, J.J., Ibers, J.A. *J. Organomet. Chem.* **1976**, *65*, 253.
(17) Stephenson, T.A., Morehouse, S.M., Powell, A.R., Heffer, J.P., Wilkinson, G. *J. Chem. Soc.* **1965**, 3632.
(18) Tsuji, J., Nisar, M., Minami, I. *Tetrahedron Lett.* **1986**, *27*, 2483.
(19) a) Minami, I., Yamada, M., Tsuji, J. *Tetrahedron Lett.* **1986**, *27*, 1805.
b) Takahashi, S., Shibano, T., Hagihara, N. *Bull. Chem. Soc. Jpn.* **1968**, *41*, 454.
(20) Krapcho, A.P., Diamanti, J., Cayen, C., Bingman, R. *Org. Synth. Coll. Vol. V*, **1973**, 198.
(21) Brown, C.A. *J. Org. Chem.* **1974**, *39*, 3913.
(22) Wanzlic, H.W., Gollmer, G., Milz, H. *Chem. Ber.* **1955**, *88*, 69.
(23) Warhoff, E.W., Martin, D.G., Johnson, W.S. *Org. Synth. Coll Vol. IV*, **1963**, 162.
(24) Corsano, S., Capito, L. *Gazz. Chim. Ital.* **1955**, *85*, 1590.
(25) Dreiding, A.S., Nickel, S.N. *J. Am. Chem. Soc.* **1954**, *76*, 3965.