

Tetrahedron 55 (1999) 2475-2486

TETRAHEDRON

Transformation of Ketones into 1-Chloro and 1,1-Dichloro-1alkenes by Means of a Polychloromethane-Titanocene(II) System

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Received 9 November 1998; accepted 28 December 1998

A bstract: The olefination of ketones using the organotitanium species formed from Cp₂Ti[P(OE1)₃]₂ and polychloromethane was studied. The reaction of the organotitanium species prepared from carbon tetrachloride with ketones produced the 1,1-dichloro-1-alkenes in good yields even when dialkyl ketones were employed. The similar olefination of ketones using chloroform afforded the 1-chloro-1-alkenes and 1,1-dichloro-1-alkenes, the ratio of which reflected the steric demand on the ketones. The titanocene chloromethylidene complex was suggested to be an active species of the reaction on the basis of the results obtained by the reaction using chloroform-d © 1999 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Carbonyl olefination is one of the most fundamental transformations in organic synthesis, and various types of unsaturated compounds are prepared by this process. For the conversion of carbonyl compounds to 1,1-dihaloalkenes, the Wittig type reaction using dihalomethylenephosphorane is frequently employed.¹ Although these reactions effect the transformation of aldehydes, aromatic ketones, and certain cyclic ketones to the corresponding 1,1-dihaloalkenes, attempts to prepare such compounds from dialkyl ketones are generally unsuccessful. For example, the reaction of dibromomethylenetriphenylphosphorane generated *in situ* from carbon tetrabromide and triphenylphosphine with 2-octanone affords the dibromoolefin in low yield, and 5-nonanone is unreactive towards the phosphorane.¹¹ One successful procedure for the conversion of ketones to 1,1-dichloro-1-alkene utilizes lithium salt of diethyl dichloromethanephosphonate.² Although cyclic ketones and certain methyl ketones are transformed into the dichlorides by this reaction, the preparation of the requisite reagent is rather complicated. The Peterson olefination using (trimethylsilyl)dichloromethyllithium was employed for the dichloromethylenation of aldehydes,³ however its application to ketones has not yet been reported.

Recently we disclosed an efficient method for the olefination of carbonyl compounds using a gem-dichlorides-Cp₂Ti[P(OEt)₃]₂ system.⁴ Unlike conventional olefination reactions, this procedure is extremely effective for the preparation of highly substituted olefins and enol ethers. These results prompted us to study the transformation of ketones 1 to haloolefins using the organotitanium reagent prepared from polyhalomethanes 2 and the low-valent titanium species Cp₂Ti[P(OEt)₃]₂ 3. In this paper we describe the preparation of 1,1-dichloro- and 1-chloro-1-alkenes 4 and 5 using carbon tetrachloride (2a) and chloroform (2b) as sources of the olefination reagents (Scheme 1). The reaction mechanism is also discussed based on the results of the olefination using chloroform-d(2c).



Scheme 1

RESULTS AND DISCUSSION

Carbon tetrachloride (2a) (2 equiv) was reduced with the low-valent titanium 3 (6 equiv), prepared by the reduction of Cp2TiCl2 with magnesium turnings in the presence of P(OEt)3 and powdered molecular sieves 4A, at room temperature for 10 min. The treatment of the resulting organotitanium species with 1,5-diphenyl-3pentanone (1c) produced dichloroolefin 4c in 59% yield (Scheme 1). When the preparation and reaction of organotitanium reagent were carried out at 0 °C, the yield was slightly increased to 63% and a small amount (16%) of the starting ketone was recovered (Table 1, entry 3). Although all the starting ketone was consumed when large excess of carbon tetrachloride and 3 were employed, the olefination product 4c was obtained in comparable yield. Similar treatment of carbon tetrabromide with the low-valent titanium 3 and 1c afforded no olefination product, and the starting ketone was recovered (85%). Under the optimized reaction conditions, the reactions of various ketones were performed. As the results in Table 1 indicate, 1,1-dichloro-1-alkenes 4 were obtained in good yields even when dialkyl ketones were employed. However, the olefination of benzophenone (1a) was exceptional and gave dichloroolefin 4a only in 22% yield though the Wittig type reaction is effective for the transformation of aromatic ketones.¹C The transformation of sterically hindered α -substituted dialkyl ketone 1h also afforded the dichloromethylidene derivative 4h in low yield (20%), and a considerable amount of the starting ketone was recovered (49%) (entry 8). It was found that 4 was contaminated with a trace amount of 1-chloro-1-alkene 5 in cases of 1a and c (entries 1 and 3). The formation of 5 is explained by the reduction of 4 with magnesium remained in the reaction mixture.

Further we studied the transformation of ketones into vinyl chlorides using chloroform (2b). We initially used technical grade 2b (99.5+% purity) after purification by passage through a column of alumina just prior to use. The reaction of 1c using 6 equiv of 3 and 2 equiv of 2b at 0 °C produced the vinyl chloride 5b in 39% yield along with a small amount of the 1,1-dichloro-1-alkene 4c. The yield of 5b increased (63%) with increasing the molar ratio of 2b (3 equiv). Furthermore we found that the yield was influenced by the purity of chloroform used; 5b was obtained in better yield (70%) when highly pure 2b (3 equiv) (99.9+%, Aldrich) was employed (Table 2, entry 2). The concomitant formation of 1,1-dichloro-1-alkene 4 was observed in most of

Entry	Ketone 1		Time / h	Product 4		Yield / %
1	O Ph [⊥] Ph	1a	19	ClCl I Ph Ph	4a	22ª
2		1b	20		4b	66
3	O Ph Ph	1c	3	CI_CI Ph Ph	4c	64 a
4	Ph~~~~	1d	2		4d	62
5	indu b	1e ^b	2		4e ^c	72
6	\sim	1f	2		4f	58
7	°	1g	1.5	CI CI	4g	74
8	O ↓ ↓ ₽h	1b	19		4h	20
9	O Ph	1i	21		4i	61
10	+()=0	1j	2	+ \) ={;	4j	58

Table 1. Olefination of Ketones 1 with Carbon Tetrachloride 2a

a) Contaminated with a trace amount (< 1%) of the chloromethylenation product 5. b) E: Z = 60: 40. c) The ratio of stereoisomers was not determined.

Entry	Ketone 1	Time / h	Product (Yield / %; Ratio of stereoisomers) ^a				
1	la	16	H_CI Ph Ph	5a (89)			
2	1c	18	H_Ci Ph Ph	5b (70)	4c (18)		
3	1d	2.5	H, Cl Ph	5 c (83; 51 : 49)	4d (15)		
4b	1g	2.5	H CI	5d (53; 62 : 38)	4g (39)		
5	1h	19	H_CI Ph	5e (56; 93 : 7)			
6	1i	19	H, Ci	5f (60; 51 : 49)	4i (22)		

Table 2. Olefination of Ketones 1 with Chloroform 2b.

a) Determined by NMR spectroscopy. b) 5d and 4g were obtained as a mixture. The yields were determined by NMR analysis.

the cases examined (Table 2). The proportion of monochloroolefin 5 and dichloroolefin 4 in this reaction seems to be dependent on the steric hindrance of ketone to the approaching organotitanium species.

In contrast to the dichloroolefination using carbon tetrachloride 2a, the monochloroolefin 5a was produced selectively in high yield by the reaction of 1a with chloroform 2b (entry 1). The reaction of sterically hindered α -substituted dialkyl ketone 1h also gave the chloroolefin 5e in good yield without formation of the corresponding dichloride (entry 5). Similarly the reactions of dialkyl ketones 1c and d afforded 5b and c with better selectivity than that of the reactions of methyl ketone 1g and cyclic ketone 1i. These results indicate that the two organotitanium species would be formed by the treatment of chloroform with Cp₂Ti[P(OEt)₃]₂ 3, and these intermediates react with ketones to produce monochlorides 5 and dichlorides 4, respectively. We have reported the carbonyl olefination using thioacetals and the low-valent titanium species 3.⁵ We proposed the titanium-carbene complex as an intermediate of this reaction on the basis of the results of its reactions with organic molecules having a carbon-carbon multiple bond⁶ and group 14 metal hydrides.⁷ It is reasonable to assume that the present reaction also proceeds through the formation of similar titanium-carbene intermediates as outlined in Scheme 2. The first step of the reaction is the oxidative addition of chloroform to the low-valent titanium 3 to form the alkyltitanium compound 7. The two types of titanium-carbene complexes 8 and 9 are produced by the further reaction of 7 with 3, in which both C-Cl and C-H bonds are cleaved. It is obvious that the reaction of dichloromethylidene complex 9 with ketones is largely affected by steric hindrance, compared with that of chloromethylene complex 8. Considering that a large excess of 3 (6 equiv) and 2b (3 equiv) were used, the observed variable proportions of 5 and 4 depending on the substituents of ketones is explicable by the difference of reactivity between 8 and 9.



Several methods for the transformation of carbonyl compounds into 1-chloro-1-alkenes with one carbon homologation have been reported. The reagent prepared from haloform and chromium(II) chloride has been employed for the stereoselective transformation of aldehydes to 1-haloolefins.⁸ The most frequently employed method for the preparation of chloroolefins from carbonyl compounds is the Wittig-type reaction using chloromethylenetriphenylphosphorane.⁹ Similarly to the other carbonyl olefinations, this Wittig-type reaction is largely affected by steric hindrance, and the yields tend to be decreased when dialkyl ketones are subjected to the reaction.^{1b} It should be noted that the present chloroolefination is a good alternative synthetic method especially for the transformation of dialkyl ketones.

We have further investigated the pathway of this reaction using chloroform-d(2c) as a source of the organotitanium species. As stated above, we tentatively assume that the low-valent titanium 3 promoted chloroolefination proceeds through the formation of carbene complexes. However the observation that both monoand dichloroolefins are produced by the olefination using chloroform do not exclude the pathway depicted in Scheme 3, in which the gem-dititanium species 10 and 10' react with a ketone 1 to produce the adducts such as 11. A similar gem-dichromium compound has been suggested as an active species of the haloolefination using a haloform-chromium(II) chloride system.⁸





McCowan and his coworkers have studied the thermal decomposition of dimethyltitanocene 12 and its deuteriated analogue.¹⁰ The thermolysis of 12 was reported to proceed through the formation of titanocene methylidene complex 13. The subsequent thermal decomposition of 13 leads to produce certain titanium compounds and methane. On the basis of the observation that the Cp ring hydrogens were incorporated into methane, they proposed that a species equivalent to $Cp(C_5H_4)$ TiMe is formed from 13 by the reversible hydrogen abstraction from a Cp ring. If the chloroolefination of ketones with chloroform-*d* 2c would take place via the formation of the deuteriated chloromethylidene complex 14, one would expect that the H/D scrambling between the hydrogens of Cp ring and chloromethylidene group proceeds to produce the new carbene complex 15 which then reacts with a ketone to afford the undeuterated olefin 5 as a byproduct (Scheme 4).



When we examined the reactions of chloroform-d 2c (purity 99.8%) with ketones, we observed the formation of the deuteriated chloroolefins 6 along with the olefins possessing no deuterium 5 (Table 3). These results suggest that the present reaction proceed through the formation of titanium carbene complex. Although the dichlorides 4 were produced, the relative ratio of dichloride / monochloride was smaller than that observed in the reactions using chloroform 2b. This may be due to the deuterium isotope effect on the formation of dichloromethylidene complex 9 by the oxidative addition of 7 to the low-valent titanium 3. It should be noted that the present reaction provides a straightforward route to 1-chloro-1-deuterio-1-alkenes.

Entry	Ketone 1	Time / h	Product (Yield / %; Ratio of stereoisomers) ^b				
1	1a	18	D_CI Ph Ph	6a (70)	5a (8)		
2	1c	18	D. Ci Ph Ph	6b (63)	5b (6)		
3	1d	б	D, Ci Ph	6c (57; 51 : 49)	5c (6; 53 : 47)	4d (9)	
4	1g	19	DCI	6d (52; 62 : 38)	5d (8; 62 : 38)	4g (17)	
5	1i	20	D_,Ci	6e (56; 52 : 48)	5f (5; 52 : 48)	4i (13)	

Table 3. Olefination of Ketones 1 with Chloroform-d 2c.^a

a) The products were obtained as a mixture. b) Determined by NMR spectroscopy.

CONCLUSION

We have established new methods for the chloro- and dichloromethylenation of ketones which are especially useful for the transformation of dialkyl ketones. The fact that the chloromethylenation using chloroform-*d* produces a significant amount of the undeuterated olefin suggests that the intermediates of the present reactions would be the titanium-carbene complexes.

EXPERIMENTAL SECTION

General. All the reactions were carried out in a dry reaction vessel under argon. All melting points were determined with a Yanaco MP-S3 micromelting point apparatus. ¹H (500 MHz) and ¹³C (125 MHz) NMR spectra were measured in CDCl₃ on Jeol ALPHA-500 instrument and are reported in parts per million from tetramethylsilane. IR spectra were recorded on a Jeol Diamond-20 FT-IR spectrometer; absorptions are reported in cm⁻¹. Elemental analyses were performed by Perkin Elmer 2400II.

Materials. For preparative thin layer chromatography (PTLC), Wakogel B-5F was used as an adsorbent. THF was distilled from sodium and benzophenone. Magnesium turnings were purchased from Nakarai Tesque Inc. (Kyoto, Japan).

Reaction of 1,5-diphenylpentan-3-one (1c) with carbon tetrachloride (2a). Finely powdered molecular sieves 4A (300 mg), magnesium turnings (73 mg, 3 mmol), and Cp₂TiCl₂ (747 mg, 3 mmol) were placed in a flask and dried by heating with a heat gun under reduced pressure (2 mmHg). Care was taken not to sublimate Cp₂TiCl₂. After cooling, THF (4 mL) and P(OEt)₃ (1.06 mL, 6 mmol) were added successively with stirring at room temperature under argon. Within 15 min, the reaction mixture turned dark green and then dark brown with slight evolution of heat. After 3 h, the flask was immersed in an ice bath and stirring was continued for 20 min. Carbon tetrachloride (2a) (0.15 mL, 1.5 mmol) was added dropwise and the reaction mixture was stirred for 10 min. Then a THF (2 mL) solution of 1c (119 mg, 0.5 mmol) was added dropwise. After being stirred for 3 h, the reaction mixture was diluted with hexane (30 mL) and the insoluble materials were filtered off through celite. The filtrate was condensed under reduced pressure. The crude product was purified by PTLC (hexane) to yield 98 mg (64%) of 1,1-dichloro-4-phenyl-2-phenethylbut-1-ene (4c).

The Physical Properties of 1,1-dichloro-1-alkenes 4. 1,1-Dichloro-2,2-diphenylethene (4a) (Entry 1, Table 1). mp 79-80.5 °C (lit.^{1c} mp 80-81 °C); ¹H NMR δ 7.26-7.37 (m, 10H); ¹³C NMR δ 119.50, 127.97, 128.25, 129.24, 139.47, 140.47; IR (KBr) 3086, 3064, 3033, 1601, 1576, 1567, 1496, 1444, 970, 858, 698, 644, 613 cm⁻¹.

1-(2,2-Dichloro-1-methylethenyl)naphthalene (4b) (Entry 2, Table 1). mp 51-52 °C; ¹H NMR δ 2.28 (s, 3H), 7.28 (dd, *J*= 7.0, 0.9 Hz, 1H), 7.44-7.54 (m, 3H), 7.72-7.90 (m, 3H); ¹³C NMR δ 23.20, 118.28, 124.63, 125.06, 125.51, 126.07, 126.52, 128.11, 128.57, 129.78, 133.71, 134.87, 138.03; IR (KBr) 3060, 3003, 2916, 1618, 1591, 1508, 1437, 852, 717, 617 cm⁻¹; Anal. Calcd for C₁₃H₁₀Cl₂: C, 65.85; H, 4.25. Found: C, 65.81; H, 4.44.

1,1-Dichloro-4-phenyl-2-phenethylbut-1-ene (4c) (Entry 3, Table 1). ¹H NMR δ 2.49-2.54 (m, 4H), 2.70-2.77 (m, 4H), 7.16-7.24 (m, 6H), 7.26-7.31 (m, 4H); ¹³C NMR δ 33.30, 35.83, 116.65, 126.17, 128.29, 128.45, 137.94, 140.90; IR (neat) 3028, 2929, 1604, 1496, 1456, 897, 748, 698, 563, 494 cm⁻¹; Anal. Calcd for C₁₈H₁₈Cl₂: C, 70.83; H, 5.94. Found: C, 70.96; H, 6.03.

1,1-Dichloro-2-phenethylhex-1-ene (4d) (Entry 4, Table 1). ¹H NMR δ 0.92 (t, *J*= 7.3 Hz, 3H), 1.27-1.47 (m, 4H), 2.16-2.29 (m, 2H), 2.45-2.54 (m, 2H), 2.68-2.76 (m, 2H), 7.12-7.34 (m, 5H); ¹³C NMR δ 13.87, 22.52, 29.31, 33.36, 33.47, 35.63, 115.59, 126.12, 128.29, 128.43, 138.82, 141.10; IR (neat) 3028, 2958, 2931, 2862, 1614, 1604, 1496, 1466, 1456, 895, 748, 698 cm⁻¹; Anal. Calcd for C₁₄H₁₈Cl₂: C, 65.38; H, 7.05. Found: C, 65.75; H, 7.15.

1,1-Dichloro-2,6,10-trimethylundec-1,5,9-triene (4e) (Entry 5, Table 1). ¹H NMR δ 1.59-1.63 (m, 4.7H), 1.67-1.71 (m, 4.3H), 1.86 and 1.87 (2s, 3H), 1.96- 2.19 (m, 6H), 2.23-2.31 (m, 2H), 5.05-5.16 (m, 2H); ¹³C NMR δ 15.89, 17.62, 17.64, 19.97, 23.34, 25.35, 25.45, 25.66, 25.70, 26.57,

26.61, 31.86, 35.49, 35.83, 39.67, 114.42, 122.64, 123.56, 124.15, 124.22, 131.36, 131.61, 134.93, 136.36, 136.43; IR (neat) 2968, 2918, 2858, 1668, 1624, 1448, 1377, 897, 831 cm⁻¹; Anal. Calcd for $C_{14}H_{22}Cl_2$: C, 64.37; H, 8.49. Found: C, 64.27; H, 8.65.

1,1-Dichloro-2-pentylhept-1-ene (4f) (Entry 6, Table 1). ¹H NMR δ 0.90 (t, J= 7.0 Hz, 6H), 1.24-1.38 (m, 8H), 1.38-1.49 (m, 4H), 2.19-2.26 (m, 4H); ¹³C NMR δ 13.98, 22.46, 26.87, 31.63, 33.45, 114.53, 139.76; IR (neat) 2956, 2927, 2873, 2860, 1614, 1466, 1379, 903, 885, 731 cm⁻¹; Anal. Calcd for C₁₂H₂₂Cl₂: C, 60.76; H, 9.35. Found: C, 61.11; H, 9.60.

1,1-Dichloro-2-methyltridec-1-ene (4g) (Entry 7, Table 1). ¹H NMR δ 0.88 (t, *J*= 6.9 Hz, 3H), 1.21-1.35 (m, 16H), 1.39-1.48 (m, 2H), 1.85 (s, 3H), 2.24 (t, *J*= 7.6 Hz, 2H); ¹³C NMR δ 14.12, 19.79, 22.71, 26.98, 29.26, 29.37, 29.45, 29.57, 29.65, 29.66, 31.93, 35.41, 113.99, 135.34; IR (neat) 2960, 2937, 2858, 1624, 1468, 897 cm⁻¹; Anal. Calcd for C₁₄H₂₆Cl₂: C, 63.39; H, 9.88. Found: C, 63.78; H, 10.15.

1,1-Dichloro-2-ethyl-3-benzylbut-1-ene (4h) (Entry 8, Table 1). ¹H NMR δ 0.99 (d, J= 7.0 Hz, 3H), 1.08 (t, J= 7.6 Hz, 3H), 2.15-2.30 (m, 2H), 2.56 (dd, J= 13.4, 8.9 Hz, 1H), 2.75 (dd, J= 13.4, , 6.1 Hz, 1H), 3.18-3.26 (m, 1H), 7.13-7.30 (m, 5H); ¹³C NMR δ 12.59, 17.19, 23.33, 39.94, 40.91, 115.60, 126.10, 128.23, 128.98, 139.77, 143.41; IR (neat) 3064, 3028, 2972, 2877, 1603, 1496, 1464, 1454, 918, 904, 741, 698 cm⁻¹; Anal. Calcd for C₁₃H₁₆Cl₂: C, 64.21; H, 6.63. Found: C, 64.46; H, 6.89.

1-Dichloromethylidene-3-phenylcyclohexane (4i) (Entry 9, Table 1). mp 45-46 °C; ¹H NMR δ 1.42-1.65 (m, 2H), 1.90-2.00 (m, 3H), 2.03-2.11 (m, 1H), 2.63 (br t, J= 12.2 Hz, 1H), 2.96 (d, J= 15.3 Hz, 1H), 3.08 (dd, J= 13.7, 1.8 Hz, 1H), 7.20-7.26 (m, 3H), 7.29-7.36 (m, 2H); ¹³C NMR δ 26.21, 31.22, 33.51, 38.79, 44.25, 112.11, 126.42, 126.71, 128.50, 137.10, 145.54; IR (KBr) 3030, 2978, 2858, 1618, 1604, 1495, 1446, 916, 865, 755, 698 cm⁻¹; Anal. Calcd for C₁₃H₁₄Cl₂: C, 64.75; H, 5.85. Found: C, 64.75; H, 6.15.

1-Dichloromethylidene-4-*tert*-butylcyclohexane (4j) (Entry 10, Table 1). mp 55-56 °C (lit.¹¹ mp 53-54.5 °C); ¹H NMR δ 0.86 (s, 9H), 1.02-1.20 (m, 3H), 1.80-1.93 (m, 4H), 2.88-3.00 (m, 2H); ¹³C NMR δ 27.43, 27.52, 31.68, 32.37, 47.50, 110.75, 137.94; IR (KBr) 2970, 2949, 2866, 1612, 1473, 1431, 1363, 870, 854 cm⁻¹; Anal. Calcd for C₁₁H₁₈Cl₂: C, 59.74; H, 8.20. Found: C, 59.36; H, 8.19.

Reaction of 1c with chloroform (2b) (Entry 2, Table 2). To an ice-cooled THF (3 mL) solution of 3 prepared from finely powdered molecular sieves 4A (200 mg), magnesium turnings (44 mg, 1.8 mmol), Cp_2TiCl_2 (448 mg, 1.8 mmol), and P(OEt)₃ (0.62 mL, 3.6 mmol) was added 2b (0.07 ml, 0.9 mmol) dropwise, and the reaction mixture was stirred for 10 min. Then 1c (72 mg, 0.3 mmol) in THF (2 mL) was added dropwise and the mixture was further stirred for 18 h. The usual workup gave 1-chloro-4-phenyl-2-phenethylbut-1-ene (5b) (57 mg, 70%) and 4c (17 mg, 18%).

The Physical Properties of 1-chloro-1-alkenes 5. 1-Chloro-2,2-diphenylethene (5a) (Entry 1, Table 2). mp 39-40 °C (lit.¹² mp 41 °C); ¹H NMR δ 6.58 (s, 1H), 7.16-7.22 (m, 2H), 7.25-7.42 (m, 8H); ¹³C NMR δ 115.83, 127.67, 127.93, 128.03, 128.16, 128.39, 129.83, 137.52, 140.07, 143.80; IR (KBr) 3076, 3059, 2927, 1593, 1576, 1495, 1442, 1032, 968, 943, 825, 808, 769, 754, 698, 627 cm⁻¹; Anal. Calcd for C₁₄H₁₁Cl: C, 78.32; H, 5.16. Found: C, 78.10; H, 5.35.

1-Chloro-4-phenyl-2-phenethylbut-1-ene (5b) (Entry 2, Table 2). ¹H NMR δ 2.31-2.38 (m, 2H), 2.52-2.58 (m, 2H), 2.69-2.79 (m, 4H), 5.83 (s, 1H), 7.10-7.16 (m, 2H), 7.16-7.25 (m, 4H), 7.25-7.33 (m, 4H); ¹³C NMR δ 32.48, 33.31, 34.16, 36.95, 113.44, 126.01, 126.06, 128.26, 128.34, 128.36,

128.40, 141.18, 141.37, 141.50; IR (neat) 3029, 2927, 2860, 1633, 1603, 1496, 1454, 822, 795, 748, 698 cm⁻¹; Anal. Calcd for C₁₈H₁₉Cl: C, 79.84; H, 7.07. Found: C, 79.49; H, 7.14.

1-Chloro-2-phenethylhex-1-ene (5c) (Entry 3, Table 2). ¹H NMR δ 0.90 and 0.93 (2t, J = 7.1 Hz, 3H), 1.24-1.48 (m, 4H), 2.02-2.09 (m, 1H), 2.22-2.29 (m, 1H), 2.33-2.39 (m, 1H), 2.46-2.54 (m, 1H), 2.68-2.77 (m, 2H), 5.79 (s, 0.49H), 5.82 (s, 0.51H), 7.14-7.25 (m, 3H), 7.25-7.32 (m, 2H); ¹³C NMR δ 13.85, 13.93, 22.28, 22.60, 29.23, 29.71, 29.96, 32.31, 33.32, 34.28, 34.75, 36.68, 112.49, 112.55, 125.93, 126.01, 128.27, 128.32, 128.39, 141.38, 141.69, 142.15, 142.19; IR (neat) 3028, 2958, 2931, 2862, 1633, 1604, 1496, 1456, 791, 744, 698 cm⁻¹; Anal. Calcd for C₁₄H₁₉Cl: C, 75.49; H, 8.60. Found: C, 75.24; H, 8.76.

1-Chloro-2-methyltridec-1-ene (5d) (Entry 4, Table 2; contaminated with 4g). ¹H NMR δ 0.88 (t, J= 6.9 Hz, 3H), 1.22-1.33 (m, 16H), 1.37-1.46 (m, 2H), 1.73 (d, J= 1.5 Hz, 0.66H), 1.76 (d, J= 1.5 Hz, 1.05H), 1.85 (s, 1.29H), 2.01-2.07 (m, 0.71H), 2.16-2.26 (m, 1.29H), 5.74-5.76 (m, 0.22H), 5.78 (q, J= 1.2 Hz, 0.35H); ¹³C NMR δ 14.12, 16.34, 20.80, 22.70, 26.77, 27.49, 29.09, 29.34, 29.42, 29.49, 29.57, 29.59, 29.62, 29.65, 29.66, 31.79, 31.92, 37.09, 111.23, 111.59, 138.94, 138.96; IR (neat) 2956, 2925, 2854, 1466, 1379, 783, 721 cm⁻¹.

1-Chloro-2-ethyl-3-benzylbut-1-ene (5e) (Entry 5, Table 2). ¹H NMR δ 1.01(d, J= 6.4 Hz, 3H), 1.02-1.08 (m, 3H), 1.99-2.14 (m, 0.14H), 2.21 (dq, J= 13.3, 7.6 Hz, 0.93H), 2.26 (dq, J= 13.3, 7.6 Hz, 0.93H), 2.45-2.54 (m, 1.86H), 2.59 (dd, J= 13.4, 8.5 Hz, 0.07H), 2.73-2.84 (m, 1H), 3.26-3.35 (m, 0.07H), 5.73 (t, J= 1.5 Hz, 0.07H), 5.77 (s, 0.93H), 7.08-7.30 (m, 5H); ¹³C NMR δ 12.33, 17.23, 18.86, 22.74, 23.66, 36.51, 40.65, 41.38, 42.10, 111.54, 112.72, 125.89, 125.99, 128.13, 128.19, 128.95, 129.04, 140.34, 146.88, 148.06; IR (neat) 3066, 3030, 2972, 2937, 2877, 1629, 1604, 1496, 1454, 810, 752, 698 cm⁻¹; Anal. Calcd for C₁₃H₁₇Cl: C, 74.81; H, 8.21. Found: C, 74.91; H, 8.50.

1-Chloromethylidene-3-phenylcyclohexane (5f) (Entry 6, Table 2). ¹H NMR δ 1.39-1.51 (m, 1H), 1.55-1.66 (m, 1H), 1.76-1.85 (m, 0.5H), 1.90-2.01 (m, 2.5H), 2.02-2.11 (m, 0.5H), 2.16-2.24 (m, 0.5H), 2.31-2.38 (m, 0.5H), 2.42-2.50 (m, 0.5H), 2.54-2.65 (m, 1H), 2.94-3.03 (m, 0.5H), 3.05-3.15 (m, 0.5H), 5.84 (t, *J*= 1.9 Hz, 0.49H). 5.86 (t, *J*= 1.8 Hz, 0.51H), 7.17-7.35 (m, 5H); ¹³C NMR δ 26.15, 27.33, 27.88, 33.50, 33.91, 34.01, 35.64, 41.38, 44.16, 45.47, 109.37, 109.49, 126.26, 126.30, 126.68, 126.77, 128.44, 128.47, 141.11, 141.24, 145.95, 146.13; IR (neat) 3066, 3031, 2937, 2859, 1641, 1604, 1495, 1448, 972, 837, 793, 752, 700 cm⁻¹; Anal. Calcd for C₁₃H₁₅Cl: C, 75.54; H, 7.31. Found: C, 75.26; H, 7.17.

Reaction of 1c with chloroform-d (2c) (Entry 2, Table 3). To an ice-cooled THF (3 mL) solution of 3 prepared from finely powdered molecular sieves 4A (200 mg), magnesium turnings (44 mg, 1.8 mmol), Cp₂TiCl₂ (448 mg, 1.8 mmol), and P(OEt)₃ (0.62 mL, 3.6 mmol) was added 2c (0.07 ml, 0.9 mmol) dropwise, and the reaction mixture was stirred for 10 min. Then 1c (72 mg, 0.3 mmol) in THF (2 mL) was added dropwise and the mixture was further stirred for 18 h. The usual workup gave a mixture of 1-chloro-4-phenyl-2-phenethyl(1-²H)but-1-ene (6b) and 5b (57 mg). The yields of 6b (63%) and 5b (6%) were determined by NMR analysis.

The Physical Properties of 1-chloro-1-deuterio-1-alkenes 6. 1-Chloro-2,2-diphenyl[2-²H]ethene (6a) (Entry 1, Table 3; contaminated with 5a) . ¹H NMR δ 6.58 (s, 0.10H), 7.17-7.42 (m, 10H); ¹³C NMR δ 115.56 (t, J= 30 Hz), 115.84, 127.68, 127.93, 128.03, 128.17, 128.39, 129.83, 137.52, 140.07, 143.70; IR (neat) 3081, 3032, 2293, 1645, 1591, 1495, 1442, 769, 758, 696, 628 cm⁻¹.

1-Chloro-4-phenyl-2-phenethyl[1-²H]but-1-ene (6b) (Entry 2, Table 3; contaminated with 5b). ¹H NMR & 2.30-2.36 (m, 2H), 2.49-2.57 (m, 2H), 2.67-2.78(m, 4H), 5.83 (s, 0.09H), 7.10-

2485

7.15 (m, 2H), 7.15-7.24 (m, 4H), 7.24-7.32 (m, 4H); 13 C NMR δ 32.46, 33.31, 34.15, 35.83, 36.89, 36.94, 113.17 (t, J= 29 Hz), 113.46, 126.00, 126.06, 128.18, 128.27, 128.30, 128.34, 128.37, 128.41, 128.46, 140.91, 141.19, 141.22, 141.37, 141.51; IR (neat) 3062, 3026, 2925, 2860, 2293, 1616, 1603, 1496, 1454, 1030, 748, 698 cm⁻¹.

1-Chloro-2-phenethyl[1-²H]hex-1-ene (6c) (Entry 3, Table 3; contaminated with 5c and 4d). ¹H NMR δ 0.87-0.95 (m, 3H), 1.19-1.48 (m, 4H), 2.05 (t, J= 7.6 Hz, 0.9H), 2.20-2.29 (m, 1.1H), 2.32-2.39 (m, 0.86H), 2.45-2.55 (m, 1.14H), 2.67-2.76 (m, 2H), 5.78 (s, 0.047H), 5.81 (s, 0.053H), 7.12-7.32 (m, 5H); ¹³C NMR δ 13.84, 13.86, 13.93, 22.28, 22.52, 22.60, 29.24, 29.31, 29.71, 29.94, 29.97, 32.29, 32.32, 33.32, 33.36, 33.48, 34.28, 34.71, 34.76, 35.63, 36.63, 36.68, 112.22 (t, J= 30 Hz), 112.59 (t, J= 30 Hz), 112.57, 115.59, 125.93, 126.02, 126.12, 128.27, 128.32, 128.39, 128.44, 138.83, 141.12, 141.39, 141.70, 142.02, 142.05, 142.16, 142.20; IR (neat) 3064, 3028, 2958, 2931, 2859, 2293, 1604, 1496, 1466, 1456, 744, 698 cm⁻¹.

1-Chloro-2-methyl[1-²H]tridec-1-ene (6d) (Entry 4, Table 3; contaminated with 5d and 4g). ¹H NMR δ 0.88 (t, J= 7.0 Hz, 3H), 1.21-1.34 (m, 16H), 1.37-1.46 (m, 2H), 1.72 (s, 0.89H), 1.75 (s, 1.45H), 1.85 (s, 0.66H), 2.04 (t, J= 7.5 Hz, 0.97H), 2.17-2.26 (m, 1.03H), 5.74-5.76 (m, 0.038 H), 5.76-5.79 (m, 0.062H); ¹³C NMR δ 14.10, 16.30, 16.34, 19.79, 20.73, 20.79, 22.70, 26.77, 26.97, 27.50, 29.11, 29.25, 29.35, 29.42, 29.50, 29.55, 29.57, 29.60, 29.65, 29.67, 29.71, 31.78, 31.81, 31.92, 33.33, 35.41, 35.87, 37.05, 37.10, 110.98 (t, J= 30 Hz), 111.25, 111.34 (t, J= 30 Hz), 111.62, 113.98, 116.70, 126.20, 128.30, 128.48, 135.38, 137.96, 138.78, 138.94, 140.93; IR (neat) 2927, 2852, 2293, 1626, 1466, 1377, 894, 756 cm⁻¹.

1-Chloro[²H]methylidene-3-phenylcyclohexane (6e) (Entry 5, Table 3; contaminated with 5f (6e : 5f = 92.3 : 7.7). ¹H NMR δ 1.39-1.50 (m, 1.04 H), 1.55-1.66 (m, 0.96 H), 1.80 (dd, J= 13.7, 4.6 Hz, 0.48H), 1.89-2.01 (m, 2.56 H), 2.06 (dd, J= 13.3, 4.6 Hz, 0.48H), 2.19 (t, J= 13.4 Hz, 0.48H), 2.35 (br d, J= 13.6 Hz, 0.52 H), 2.45 (br d, J= 13.4 Hz, 0.48 H), 2.54-2.64 (m, 1 H), 2.98 (br d, J= 13.7 Hz, 0.48 H), 3.10 (br d, J= 13.4 Hz, 0.52 H), 5.84 (t, J= 1.8 Hz, 0.037 H), 5.86 (t, J= 1.8 Hz, 0.04H), 7.18-7.34 (m, 5 H); ¹³C NMR δ 26.14, 27.32, 27.84, 27.87, 33.44, 33.49, 33.91, 34.01, 35.61, 41.33, 41.38, 44.16, 45.46, 109.09 (t, J= 30 Hz), 109.22 (t, J= 30 Hz), 109.37, 109.49, 126.26, 126.30, 126.67, 126.76, 128.43, 128.45, 140.95, 141.09, 141.23, 145.95, 146.12; IR (neat) 3062, 3027, 2933, 2891, 2291, 1628, 1603, 1495, 1448, 972, 955, 744, 698 cm⁻¹.

Acknowledgment. This work was supported by a Grant-in-Aid for Scientific Research on Priority Area No. 10125209 from the Ministry of Education, Science, Sports, and Culture, Japan.

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