107. Dimeric Metal Complexes as Mediators for Radical C–C Bond-Forming Reactions

by **Bernd Giese*** and **Gebhard Thoma**

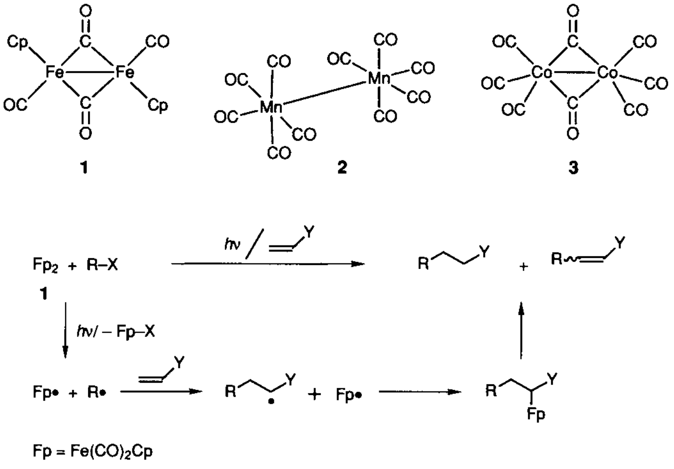
Institut für Organische Chemie der Universität Basel, St. Johanns-Ring 19, CH–4056 Basel

(19.VI.91)

Irradiation of dicarbonyl(η^5-cyclopentadienyl)iron dimer **1** or decacarbonyldimanganese (**2**) in the presence of alkyl halides leads to C-centered radicals which can be trapped by alkenes and yields saturated and/or unsaturated addition products. Carbon radicals are generated *via* halogen abstraction by the initially formed metal-centered radicals resulting from homolysis of the metal–metal bond of dimeric mediators **1** and **2**. No reaction occurs using octacarbonyldicobalt (**3**).

1. Introduction. – Irradiation of dimeric metal complexes in the presence of alkyl halides can lead to metal halogen complexes [1] *via* halogen abstraction by the initially formed 17-electron metal-centered radicals [2]. In the case of dicarbonyl(η^5-cyclopentadienyl)iron dimer **1** (*Scheme 1*), we have recently shown that I-abstraction from alkyl iodides generates free alkyl radicals which can be used in organic synthesis [3]. In the presence of alkenes, these radicals are trapped and form adduct radicals; subsequent recombination with Fe-centered radicals leads to adduct complexes. Solvolysis of the adduct complexes competes with β-elimination, resulting in saturated and/or unsaturated addition products.

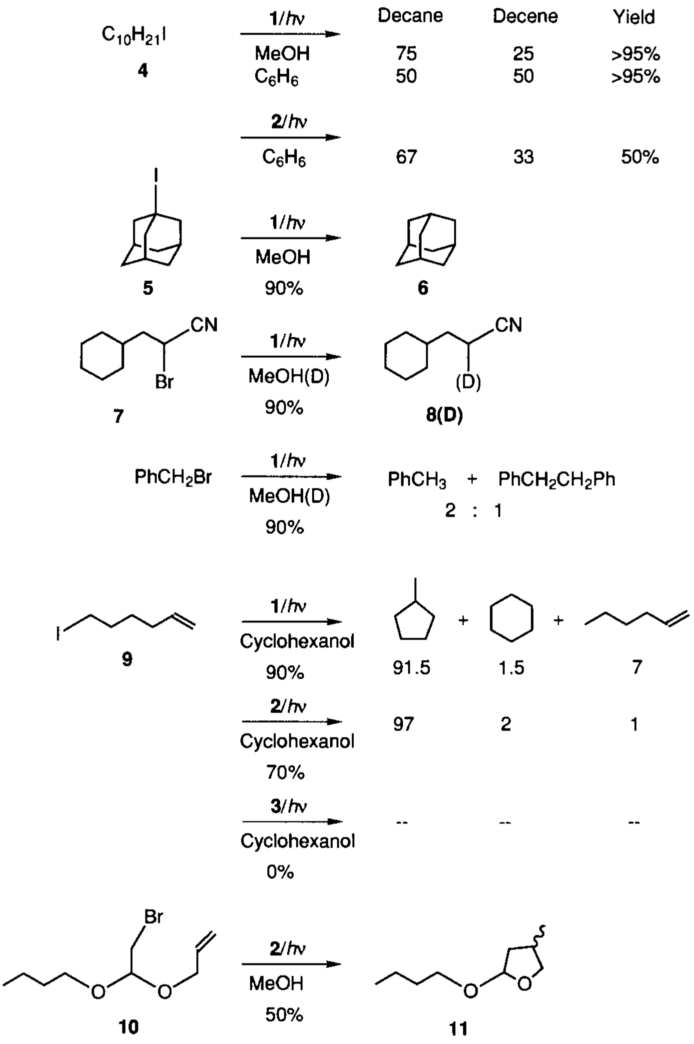
Scheme 1



Here, we present more detailed experimental data for this new 'iron method', as well as experiments using decacarbonyldimanganese (**2**) and octacarbonyldicobalt (**3**) as mediators.

2. Results and Discussion. – Alkyl iodides or activated bromides can be reduced upon irradiation of the iron complex **1**. Decyl iodide (**4**) produces decane and decene isomers almost quantitatively (*Scheme 2*). In CH_3OD, decane is found to be 70% monodeuterated. 1-Adamantyl iodide (**5**) yields adamantane (**6**). The degree of deuteration in CH_3OD is 80%. Activated bromonitrile **7** is reduced to produce **8** which is quantitatively monodeuterated,

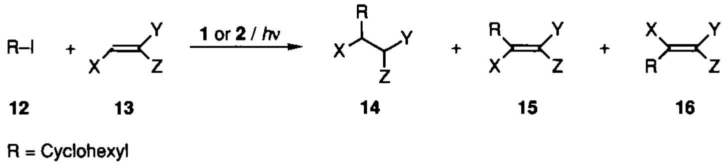
Scheme 2



if the reaction is carried out in CH_3OD. Photolysis of the iron complex **1** in the presence of $PhCH_2Br$ leads to toluene and bibenzyl in a 2:1 ratio. Irradiation of hex-5-enyl iodide (**9**) results in the formation of methylcyclopentane, cyclohexane, and hex-1-ene. Five- and six-membered rings are produced in a 98:2 ratio, which is typical for cyclization of hex-5-enyl radicals [4]. Similar results are obtained using pentacarbonyldimanganese (**2**) as mediator. With **2**, cyclization of bromo acetal **10** forms cyclized product **11**. Iron complex **1** does not react with bromide **10**. Thus, the Mn-centered radical generated from complex **2** is more reactive than the Fe radical. Octacarbonyldicobalt (**3**) is completely unreactive, even towards activated halides.

Intermolecular C–C bond-forming reactions are also possible using the 'iron method'. Thus, photolysis of cyclohexyl iodide (**12**) and various electron-poor alkenes **13** in the presence of dimeric iron complex **1** leads to saturated addition products **14** and unsaturated substitution products **15** and **16** (*Scheme 3*).

Scheme 3



The data in *Table 1* show that protic solvents and electron-withdrawing groups at the alkene give saturated compounds **14**, whereas less electron-withdrawing substituents and

Table 1. *Photolysis of Metal Complexes* **1** *or* **2** *in the Presence of Cyclohexyl Iodide* (**12**) *and Alkenes* **13** (see *Scheme 3*)

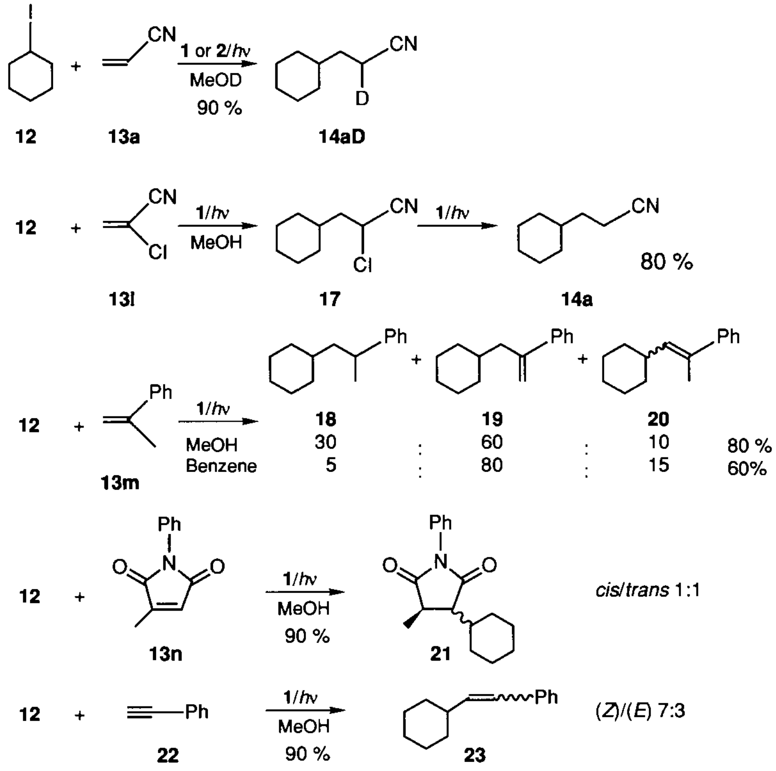
Alkene **13**				Metal complex	Solvent	**14**	**15**		**16**	Yield [%]
	X	Y	Z							
a	H	CN	H	1	MeOH	100	–		–	90
					CH_2Cl_2	55	18		27	80
					C_6H_6	50	20		30	75
				2	MeOH	94	3		3	45
					CH_2Cl_2	93	3		4	60
					C_6H_6	93	2		5	30
b	H	CO_2Me	H	1	MeOH	100	–		–	55
c	H	CN	OEt	1	AcOH	88		12		55
					MeOH	88		12		80
					C_6H_6		50	50		65
d	H	Ph	H	1	MeOH	40	26		34	50
					C_6H_6	5	37		58	45
e	H	Ph	Ph	1	MeOH	67		33		60
					C_6H_6		10	90		55
f	Me	CN	H	1	MeOH	100	–		–	50
g	H	CO_2Et	CO_2Et	1	MeOH	100	–		–	75
h	Me	CO_2Et	CO_2Et	1	MeOH	100	–		–	55
i	i-Pr	CO_2Me	CO_2Me	1	MeOH	100	–		–	15
k	*t*-Bu	CO_2Me	CO_2Me	1	MeOH	–	–		–	–

aprotic solvents favor the unsaturated products **15** and **16**. Alkyl groups X at the reactive C-center (*cf.***13f**, **13h–k**) lead to lower yields as their bulkiness increases. *t*-Bu-substituted methylidenemalonate **13k** gives no addition products. C–C Bond formation can also not be achieved with electron-rich alkenes such as methyl vinyl ether.

The reaction of cyclohexyl iodide (**12**) with acrylonitrile (**13a**) using the complex **2** as mediator yields saturated product **14a** and unsaturated products **15a** and **16a**. However, no solvent dependence of the product ratio was observed. Even in protic solvents, such as CH_3OH, small amounts of unsaturated compounds **15a** and **16a** are produced. In CH_2Cl_2 or benzene, the ratio remains unchanged, but the yields are lower than those obtained using the iron complex **1**. Probably, the adduct radicals formed *via* alkyl-radical addition to the alkene are trapped less efficiently using the Mn than the Fe complex. The Fe–Fe bond of **1** is weaker (96 kJ/mol [5]) than the Mn–Mn bond of **2** (150 kJ/mol [6]). Therefore, the concentration of Mn radicals should be lower than that of Fe radicals, leading to less effective trapping of adduct radicals by the Mn radicals.

The reaction of **12** with **13a** in CH_3OD leads quantitatively to deuterated addition product **14aD** using either mediators **1** or **2** (*Scheme 4*). Irradiation of **1** in the presence of cyclohexyl iodide (**12**) and α-chloroacrylonitrile (**13l**) yields nitrile **14a** which is presumably formed *via* reduction of the initially produced chloronitrile **17**. Reaction of α-methylstyrene (**13m**) leads to unsaturated compounds **19** and **20** as the main products, with

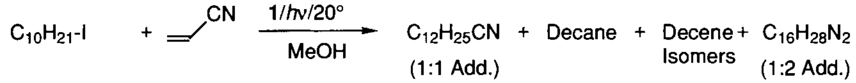
Scheme 4



the terminal alkene **19** as the favored regioisomer. Cyclic alkene **13n** gives addition product **21** in a 1:1 *cis/trans* ratio and phenylacetylene (**22**) yields styrene derivatives **23** in a 7:3 (*Z*)/(*E*) ratio.

The influence of the alkene concentration on the product ratio and the yield was studied by irradiation of decyl iodide (**4**) and acrylonitrile (**13a**) with the iron complex **1**, yielding nitrile **24**, decane, and small amounts of decene isomers (*Scheme 5*). The best yields of addition product **24** are obtained using 10 to 20 equiv. of the alkene. Lower alkene concentrations lead to increasing amounts of decane, whereas higher alkene concentrations result in the formation of 1:2 addition product **25** which can be detected by GC/MS.

Scheme 5

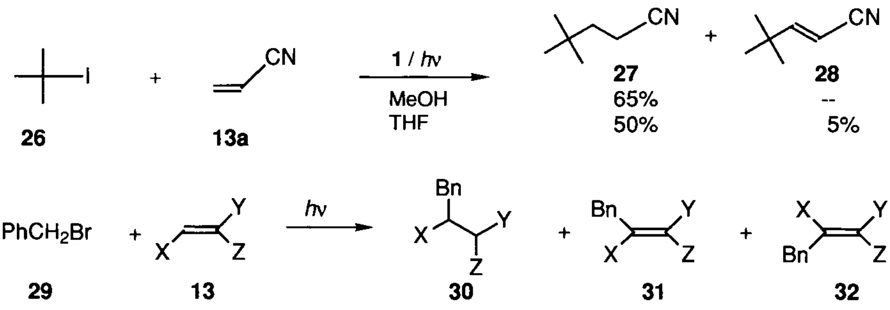


4 **13a** **24** **25**

13a / **4**	**24** [%]	Decane [%]	Decene Isomers [%]	**25** [%]
1	47	50	3	-
2	63	35	2	-
5	78	21	1	-
10	83	16	1	-
20	85	12	-	1
50	85	5	-	5

The reaction of *t*-BuI (**26**) with **13a** in MeOH using the iron complex **1** as mediator leads exclusively to saturated product **27** (*Scheme 6*). Even in THF, only a small amount of unsaturated compound **28** is formed. Photolysis of the iron complex **1** in the presence of $PhCH_2Br$ (**29**) and electron-poor alkenes yields saturated products **30** and/or unsaturated addition products **31** and **32** depending on the solvent and the substituents on the alkene (*Table 2*).

Scheme 6



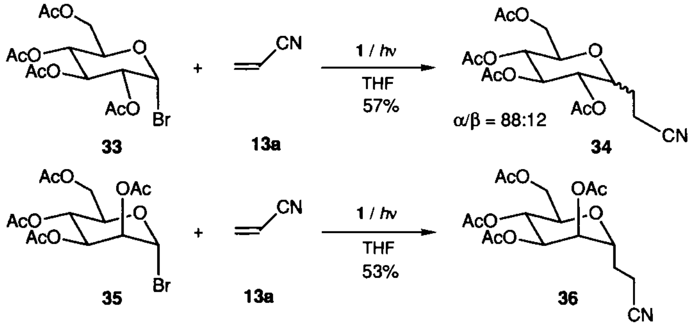
Bn = $PhCH_2$

Table 2. *Photolysis of the Iron Complex* **1** *in the Presence of Benzyl Bromide* (**29**) *and Alkenes* **13** (see *Scheme 7*)

Alkene 13				Solvent	30	31	32	Yield [%]
	X	Y	Z					
a	H	CN	H	MeOH	100	–	–	65
				C_6H_6	55	25	20	60
b	H	CO_2Me	H	MeOH	98	–	2	55
e	H	Ph	Ph	C_6H_6		2	98	50
f	Me	CN	H	C_6H_6	100	–	–	50
o	Me	CO_2Et	H	C_6H_6	100	–	–	40
p	CN	CN	H	THF	100	–	–	50

Glycosyl bromides **33** and **35** can also be used for radical C–C bond formation. In the presence of **13a**, bromide **33** leads to *C*-glycoside **34** with an *α*/*β* ratio of 88:12, whereas **35** gives exclusively the *α*-isomer **36** (*Scheme 7*). The *α*/*β* ratios of **34** and **36** are identical to those obtained using Bu_3SnH as mediator [7].

Scheme 7



3. Conclusion. – Dimeric metal complexes are useful mediators in inter- and intramolecular radical addition reactions to C–C *π*-bonds. Various halides can be used as radical precursors. Both saturated and unsaturated addition products are formed using the iron complex **1**, depending on the choice of solvent and substituents at the alkene. The Mn radical generated from the dimeric manganese complex **2** is more reactive towards alkyl halides, but the yields of the addition products are lower than those with the iron complex **1**.

This work was supported by the *Volkswagen-Stiftung* and the *Deutsche Forschungsgemeinschaft*.

Experimental Part

General. The irradiation experiments were carried out with an *Osram Power Star HQI T 250/D* sunlamp in *Pyrex* vessels that were cooled with H_2O. The reaction mixtures were irradiated through *Pyrex* and H_2O. Chromatography utilized silica gel: *C 560KV* 35–70 µm, (*Chemische Fabrik Uetikon*) or aluminium oxide: *507C* neutral (*Fluka*, activity III according to *Brockmann*). GC: *Carlo Erba 6000* with flame ionization detector coupled to a *Shimadzu C-R4A* integrator (conditions: 25 m *OV-1701* or 25 m *SE-30*, 50° to 260° at 10°/min). GC/MS: *Hewlett-Packard 5790A* gas chromatograph coupled to a *Hewlett-Packard 5970A* mass-selective detector (conditions; 25 m, *SE-30*, 50° to 260° at 10°/min). IR: *Perkin Elmer 781* spectrophotometer. ^1H- and ^{13}C-NMR: *Varian Gemini 300* (TMS as internal standard). MS: *VG 70-250* or a *Varian MAT 212*.

Reduction Reactions. A soln. of the halide (1.0 mmol) and metal complex **1** or **2** (1-2 mmol) in degassed solvent (20 ml) was irradiated at 15–20° for 2–3 h. The solvent was removed *in vacuo* and the residue extracted with Et_2O (20 ml). Chromatography on aluminium oxide with pentane/Et_2O (starting with pentane, then pentane/Et_2O 20:1–5:1) gives the products. Adamantane (**6**) was eluted with pure pentane. Decane and decene isomers were analyzed by GC/MS. Solvents and yields are given in *Scheme 2*. The degrees of deuteration were determined by ^1H-NMR and/or MS. Using **1** as mediator, ferrocene, dicarbonyl(η^5-cyclopentadienyl)iodo- and -bromoiron were isolated in addition to the products of C–C bond formation. All products are known compounds.

Intramolecular C–C Bond-Forming Reactions. Reaction with Hex-5-enyl Iodide (**9**). A soln. of **9** (210 mg, 1.0 mmol) and metal complex **1**, **2**, or **3** (1–2 mmol) in degassed cyclohexanol (20 ml) was irradiated at 15° for 12 h. The cyclized products were analyzed by comparison of their GC/MS with authentic samples. In the case of octacarbonyldicobalt, starting material **9** was not consumed even at 60°.

Reaction with Bromoacetaldehyde Allyl Butyl Acetal (**10**) [8]. A soln. of **10** (240 mg, 1.0 mmol) and **2** (400 mg, 2.0 mmol) in degassed MeOH (20 ml) was irradiated at 15° for 2 h. The solvent was removed *in vacuo* and the residue extracted with Et_2O (20 ml). Chromatography on aluminium oxide with pentane/Et_2O (starting with pentane, then pentane/Et_2O 20:1–5:1) gives 79 mg of product **11** in 50% yield which was characterized by comparison with an authentic sample [8].

Intermolecular C–C Bond-Forming Reactions. A soln. of halide (1.0 mmol), alkene (10–20 mmol), and metal complex **1**, **2**, or **3** (1–2 mmol) in degassed solvent (20 ml) was irradiated at 15–20° for 2–3 h. The solvent was removed *in vacuo* and the residue extracted with Et_2O (20 ml). Chromatography on aluminium oxide with pentane/Et_2O (starting with pentane, then pentane/Et_2O 20:1–5:1) yields the products. Solvents and yields are given in *Schemes 3–7* and *Tables 1* and *2*. The degree of deuteration was determined by ^1H-NMR. The *C*-glycosides **34** and **36** were purified by flash chromatography on silica gel with pentane/Et_2O 1:1.

3-Methyl-4-phenylbutanenitrile (**30f**): IR (film): 2240. ^1H-NMR (300 MHz, $CDCl_3$): 1.13 (*d*, *J* = 6.6, CH_3); 2.15–2.32 (*m*, 2 H–C(2), H–C(3)); 2.67 (*d*, *J* = 7.1, 2 H–C(4)); 7.15–7.35 (*m*, Ph). ^{13}C-NMR (75 MHz, $CDCl_3$): 19.3 (CH_3); 23.4 (C(2)); 32.4 (C(3)); 41.9 (C(4)); 118.8 (CN); 126.7 (C(4')); 128.8 (C(3'), C(5')); 129.2 (C(2'), C(6')); 139.2 (C(1')). MS ($C_{11}H_{13}N_5$): calc.: 159.1047; found: 159.1048.

Ethyl 3-Methyl-4-phenylbutanoate (**30o**): IR (film): 1740. ^1H-NMR (300 MHz, $CDCl_3$): 0.95 (*d*, *J* = 5.8, CH_3); 2.15 (*m*, H–C(3)); 2.30 (*m*, 2 H–C(2)); 2.51 (*dd*, *J* = 13.0, 7.4, 1 H–C(4)); 2.62 (*dd*, *J* = 13.0, 7.4, 1 H–C(4)); 3.65 (*s*, CH_3O); 7.15–7.31 (*m*, Ph). ^{13}C-NMR (75 MHz, $CDCl_3$): 19.4 (CH_3); 32.1 (C(2)); 40.7 (C(3)); 42.9 (C(4)); 126.2 (C(4')); 128.4 (C(3'), C(5')); 129.4 (C(2'), C(6')); 140.4 (C(1')); 173.8 (C(1)). MS ($C_{12}H_{16}O_2$): calc.: 192.1164; found: 192.1150.

2-Benzylbutanedinitrile (**30p**): IR (film): 2220. ^1H-NMR (300 MHz, $CDCl_3$): 2.64 (*m*, 2 H–C(3)); 3.02 (*m*, H–C(2), $PhCH_2$); 7.24–7.42 (*m*, Ph). ^{13}C-NMR (75 MHz, $CDCl_3$): 20.0 (C(3)); 30.0 (C(2)); 36.9 ($PhCH_2$); 115.5 (C(1)); 118.5 (C(4)); 128.0 (C(4')); 129.0 (C(3'), C(5')); 129.1 (C(2'), C(6')); 134.4 (C(1')). EI-MS: 170 (M^+), 91. Anal. calc. for $C_{11}H_{10}N_2$ (170.22): C 77.62, H 5.92, N 16.46; found: C 77.35, H 6.02, N 16.19.

All other products are known compounds.

REFERENCES

[1] C. Giannotti, G. Merle, *J. Organomet. Chem.* **1976**, *105*, 97; H. B. Abrahamson, M. S. Wrighton, *J. Am. Chem. Soc.* **1977**, *99*, 510; H. B. Abrahamson, M. S. Wrighton, *Inorg. Chem.* **1978**, *17*, 1003; J. V. Caspar, T. J. Meyer, *J. Am. Chem. Soc.* **1980**, *102*, 7794; D. R. Tyler, M. A. Schmidt, H. B. Gray, *ibid.* **1983**, *105*, 6018.

[2] M. C. Baird, *Chem. Rev.* **1988**, *88*, 1217; S. Di Marco, S. Sostero, O. Traverso, D. Rehorek, T. Kemp, *Inorg. Chim. Acta* **1990**, *176*, 107; R. D. Moore, M. B. Simpson, M. Poliakoff, J. J. Turner, *J. Chem. Soc., Chem. Commun.* **1984**, 972; A. J. Dixon, M. Healy, M. Poliakoff, J. J. Turner, *ibid.* **1986**, 994; A. J. Dixon, S. J. Gravelle, L. J. van de Burgt, M. Poliakoff, J. J. Turner, E. Weitz, *ibid.* **1987**, 1023; A. Hudson, M. F. Lappert , P. W. Lednor, B. K. Nicholson, *ibid.* **1974**, 966; A. Hudson, M. F. Lappert, B. K. Nicholson, *J. Chem. Soc., Dalton Trans.* **1977**, 551.

[3] G. Thoma, B. Giese, *Tetrahedron Lett.* **1989**, *30*, 2907.

[4] A. L. J. Beckwith, C. H. Schiesser, *Tetrahedron* **1985**, *41*, 3925.

[5] A. R. Cutler, M. Rosenblum, *J. Organomet. Chem.* **1976**, *120*, 87.

[6] L. I. B. Haines, D. Hopgood, A. E. Poe, *J. Chem Soc. (A)* **1968**, 421; D. M. Chowdhury, A. E. Poe, K. R. Sharma, *J. Chem. Soc., Dalton Trans.* **1977**, 2351.

[7] B. Giese, *Angew. Chem.* **1989**, *101*, 993; *ibid. Int. Ed.* **1989**, *28*, 969.

[8] Y. Ueno, O. Moriya, K. Chino, M. Watanabe, M. Okawara, *J. Chem. Soc., Perkin Trans. 1* **1986**, 1351.