Cu(II) complex is indicated, showing no interaction between Cu(II) ions, in which an open conformation of L as found for **2** is presumed for **3**.

When dissolved in water at pH ~6, **3** is transformed into a closely related complex which can be isolated independently.[15] This new complex 4 shows optical transitions (in PC) at 685 (ϵ_{Cu} ~475), 585 (sh), 447 (ϵ_{Cu} ~8000), 375 (ϵ = ~4200), and 315 nm (ϵ ~1600). Analysis and infrared data indicate the presence of the complex $[\langle Cu(II)\cdots(OH)\cdots Cu(II)\rangle](BF_4)_3$ as well as solvate molecules of PC, H_2O, and ethyl acetate. The preliminary X-ray structure of **4**[16] is shown in Figure 2. The two copper atoms, each in a distorted five-coordinate geometry, are bridged by a single hydroxo group. The dimer unit possesses a symmetry plane which is perpendicular to the phenyl ring and contains the oxygen atom of the bridge. The geometry around each Cu(II) ion is approximately square pyramidal. The basal plane defined by O(1), S(4), N(1), and S(10) is distorted toward a tetrahedral configuration as indicated by the angles S–Cu–S = 159.5 (7) and N–Cu–O = 167.2 (9)°. The apical position is occupied by the ether O(7). Most important, L is now in its "ear-muff" or closed conformation with the single bridging hydroxo group holding the two Cu(II) atoms at a distance of 3.384 (9) Å. The Cu–O–Cu angle of 132.2 (4)° is much larger than those previously observed in planar di-μ-hydroxo copper complexes which range from 95 to 105°.[17]

Despite the similar optical properties of **3** and **4**, **4** has entirely different magnetic and ESR behavior. The ESR spectrum of powdered samples of **4** at 293 K shows typical triplet state features, with $\Delta m = \pm 1$ transitions at $g = 2.094$ and a much weaker $\Delta m = 2$ transition at half-field characteristic of the dimeric unit.[18]

The temperature dependence of the magnetic susceptibility was monitored through measurements of changes in the area of the $\Delta m = 2$ ESR signal with temperature[19] in the range 333 to 103 K. A plot of log IT against $1/T$, where I is the product of the intensity of the signals and the line width square, is linear with a slope of $|2J|/k$. The average $-2J$ value thus obtained by three measurements on three different samples is 850 cm^{-1}. Similarly, the temperature variation of the magnetic susceptibility has been studied to determine the magnitude of the exchange integral by using a Faraday-type magnetometer from 300 to 1.3 K. The data are typical of two strongly antiferromagnetically coupled ($S = {}^1/_2$) systems which exhibit a subnormal magnetic moment of 0.48 μ_B/Cu at room temperature. Furthermore, the magnetic susceptibilities measured from 300 to 1.3 K allow the singlet–triplet separation energy of $-2J$ to be calculated[20] as 820 cm^{-1}, which is in good agreement with the ESR data.

Binuclear copper complexes bridged by a single hydroxo group are rare.[21-26] Complex **4** is the first example for which the X-ray structure as well as the detailed magnetic measurements have been reported. The very strong antiferromagnetic interaction observed in **4** would seem to be related to the large Cu–O–Cu angle as well as to the presence of the bridging OH group in both basal planes of the binuclear unit thus allowing good overlap with the $d_{x^2y^2}$ orbitals of both Cu atoms.[27] These results lead to two important conclusions: (a) the conformational flexibility of this type of ligand and the "face-to-face" approach of the two nucleating centers allow the observation of sensitive structural and physical changes at the binuclear site; (b) a single bridging phenolate from a tyrosine residue could adequately satisfy the structural and magnetic requirements of binuclear type III copper system. We are currently trying to synthesize such a structural unit.

Acknowledgment. This work was supported by the "Centre National de la Recherche Scientifique" and the D.G.R.S.T. (No. 76.7.1145). We thank Dr. J. J. André and Dr. G. Krill for assistance with ESR and magnetic susceptibility measurements and helpful discussions.

---

[15] By treatment of **3** in PC with 3-Å molecular sieves and slow addition of ethyl acetate, small and poorly formed crystals of **4** were obtained.

[16] **4** crystallizes in the monoclinic space group $P2/m$ with $a = 18.899$ (6), $b = 13.016$ (5), $c = 8.763$ (3) Å; $\beta = 98.98(2)°$; $V = 2129.5$ Å^3; $\rho_{expt} = 1.65$, $\rho_{calcd} = 1.64$ g cm^{-3}; $Z = 2$ formula units per cell. A total of 2917 independent nonzero reflections were measured on a Philips PW 1100 diffractometer. 2394 reflections with $I > 3\ \sigma(I)$ were used for solving the structure. At the present stage of refinement the value of the conventional discrepancy index is $R_f = 0.16$. The macrocyclic binuclear cation is clearly defined and separated form the solvate molecules (PC, H_2O, ethyl acetate) and BF_4^- anions which are very disordered at statistically occupied positions. This extensive disorder, however, does not affect the structural details of the complex cation. Further refinement is in progress.

[17] See, for example: (a) Charlot, M. F.; Jeannin, S.; Jeannin, Y.; Kahn, O.; Lucrece, J.; Baul, A.; Martin-Frere, J. *Inorg. Chem.* **1979**, *18*, 1675. (b) Hodgson, D. J. *Prog. Inorg. Chem.* **1975**, *19*, 173. (c) Crawford, V. H.; Richardson, H. W.; Wasson, J. R.; Hodgson, D. J.; Hatfield, W. E. *Inorg. Chem.* **1976**, *15*, 2107.

[18] Boas, J. F.; Dunhill, R. H.; Pilbrow, J. R.; Srivastava, R. C.; Smith, T. D. *J. Chem. Soc. A* **1969**, 94.

[19] See: Wasson, J. R.; Shyr, C. I.; Trapp, C. *Inorg. Chem.* **1968**, *7*, 469.

[20] The experimental data closely follow the Bleaney–Bowers equation giving the molecular susceptibility as a function of the temperature for a Cu(II) dimer.

$$\chi_M = \frac{2g^2\beta^2N}{3kT}\left[\frac{1}{1 + {}^1/_3 \exp(-2J/kT)}\right] + 2N\alpha$$

where $2N\alpha = 120$ and g is determined from the ESR measurements. The magnetic data have been corrected for monomeric paramagnetic impurities which were detected from the variable-temperature ESR studies (maximum amount = 5%).

[21] Haddad, M. S.; Hendrickson, D. N. *Inorg. Chim. Acta* **1978**, *28*, L121–122.

[22] Drew, M. G. B.; McCawn, M.; Nelson, S. M. *J. Chem. Soc., Chem. Commun.* **1979**, 481.

[23] Grzybowski, J. J.; Merrell, P. H.; Urbach, F. L. *Inorg. Chem.* **1978**, *17*, 3078.

[24] Barraglough, C. G.; Brookes, R. W.; Martin, R. L. *Aust. J. Chem.* **1974**, *27*, 1843.

[25] Okawa, H.; Tokii, T.; Nonaka, Y.; Muto, Y.; Kida, S. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 1462.

[26] Dickson, J. E.; Robson, R. *Inorg. Chem.* **1974**, *13*, 1301.

[27] Hay, P. J.; Thibeault, J. C.; Hoffmann, R. *J. Am. Chem. Soc.* **1975**, *97*, 4884.

Photoreduction of 5-Bromouracil. Ionic and Free-Radical Pathways

Barry J. Swanson, J. Christopher Kutzer, and Tad H. Koch*

Department of Chemistry, University of Colorado
Boulder, Colorado 80309

Received October 24, 1980

Replacement of thymine in DNA by 5-bromouracil (BU) yields DNA with enhanced photosensitivity with respect to single strand breaks[1] and DNA–protein photocrosslinking.[2] Little, however, is known about the chemistry of crosslinking to proteins. Sulfhydryl compounds such as cysteine[3] and indole containing compounds such as tryptophan derivatives[4] have been shown to couple photochemically with 5-bromouracil and 5-bromouradine. Reaction with tryptophan derivatives is sensitized by acetone, quenched by 1,3-pentadiene, and proposed to occur via an electron-transfer mechanism.[4]

We have investigated the photoreduction of 5-bromouracil to uracil in deuterium labeled 2-propanol solvents to clarify the primary photochemical processes of 5-bromouracil which lead to DNA photosensitivity. The literature often describes the primary photochemical event as homolysis of the vinyl carbon–bromine bond.[5] We report here evidence which suggests that 5-bromouracil is reduced to uracil via a radical pathway in the singlet

---

[1] Hutchinson, F. *Quart. Rev. Biophys.* **1973**, *6*, 201.

[2] Lin, S. Y.; Riggs, A. D. *Proc. Natl. Acad. Sci. U.S.A.* **1974**, *71*, 947.

[3] Varghese, A. J. *Photochem. Photobiol.* **1974**, *20*, 461.

[4] Saito, I.; Ito, S.; Matsuura, T. *J. Am. Chem. Soc.* **1978**, *100*, 2901; *Tetrahedron Lett.* **1978**, 2585. Ito, S.; Saito, I.; Matsuura, T. *J. Am. Chem. Soc.* **1980**, *102*, 7535.

[5] Campbell, J. M.; von Sonntag, C.; Schulte-Frohlinde, D. *Z. Naturforsch. B* **1974**, *29B*, 750.

0002-7863/81/1503-1274$01.25/0

Table I. Photolysis of 5-Bromouracil in Deuterated 2-Propanol Solvents

solvent	light source	BU destruction, %	deuterium incorporation in U,[a] %
$(CH_3)_2CDOH$	low-pressure Hg[b]	19	56
$(CD_3)_2CHOH$	low-pressure Hg[b]	28	9
$(CH_3)_2CHOD$	low-pressure Hg[b]	20	29
$(CH_3)_2CHOD/(CH_3)_2CO$	medium-pressure Hg[c]	31	68
$(CH_3)_2CHOD/(CD_3)_2CO$ 2:1 v/v	medium-pressure Hg[c]	48	81
$(CH_3)_2CHOD$ + 0.033 M *cis*-1,3-pentadiene	low-pressure Hg[b]	34	2

[a] The percent deuterium incorporation was measured at the 5 position of uracil by 360-MHz ^1H NMR spectroscopy. The concentration of BU was 0.0068 M. Most of these experiments were performed more than once, and the percent deuterium incorporation is independent of the percent BU destruction. [b] A quartz cell was used. [c] A Pyrex cell was used.

Table II. Quantum Yield of Uracil Formation with Acetone Sensitization[a]

[acetone], M	[BU], M	quantum yield of U formation	light absorbed by acetone, %
6.9	6.2×10^{-3}	0.19	>97
6.9	4.6×10^{-3}	0.20	>97

[a] Samples of 5-bromouracil in 2-propanol–acetone solvent (2:1 v/v) were irradiated at 313 ± 2 nm isolated with a Bausch and Lomb monochromator.

manifold and via an ion-radical pathway in the triplet manifold.

Irradiation at 254 nm of 5-bromouracil (0.0068 M) to low conversion in 2-propanol solvent cleanly gives uracil with a quantum yield of formation of 1.9×10^{-2}.[6] Acetone and hydrogen bromide are byproducts of the reaction. With higher conversion uracil absorbs a portion of the incident light and photochemically forms a solvent adduct, 5,6-dihydro-6-[(hydroxymethyl)ethyl)]-uracil.[7] In deuterated 2-propanol solvents both uracil and 5-deuteriouracil are formed as reported in Table I. High deuterium incorporation in the 5 position of uracil occurs upon direct irradiation at 254 nm of BU in 2-deuterio-2-propanol solvent and upon acetone-sensitized irradiation of BU with a Pyrex filter in 2-propanol-*d* solvent. Deuterium incorporation is further enhanced upon irradiation through a Pyrex filter of BU in 2-propanol-*d*–acetone-d_6 solvent mixture (2:1 v/v). Lower deuterium incorporation from irradiation in 2-propanol-*d*–acetone solvent mixture is presumed to result from hydrogen bromide catalyzed exchange of the deuterium of 2-propanol-*d* with the protons of acetone. The quantum yield of uracil formation upon acetone sensitization is 0.20 as shown in Table II. Efficient energy transfer from triplet acetone to bromouracil occurs since the quantum yield is BU concentration independent.

The following control experiments indicate that deuterium incorporation from irradiation of BU in 2-propanol-*d* solvent does not result from a dark reaction catalyzed by hydrogen bromide. When 1 equiv of deuteriobromic acid, prepared from hydrogen bromide and deuterium oxide, and uracil were stirred in 2-propanol-*d* solvent for 6 h, the recovered uracil showed no deuterium incorporation at the 5 position. In a second control experiment, a solution of BU in 2-propanol-*d* solvent was irradiated at 254 nm to approximately 25% conversion. One-half of the irradiation solution was analyzed immediately for deuterium incorporation and the other half was heated at 50 °C for 25 min prior to analysis. The uracil in both solutions was found to contain identical deuterium incorporation at the 5 position.

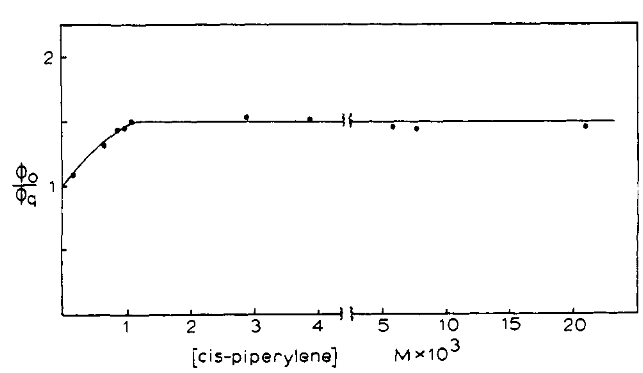


Figure 1. The Stern–Volmer plot for quenching of uracil formation by *cis*-piperylene. 5-Bromouracil was 0.0043 M in 2-propanol solvent and solutions were irradiated at 254 nm.

We also argue that deuterium incorporation in the 5 position of uracil does not occur from a photochemical reaction between uracil, deuterium bromide, and 2-propanol-*d* because the percent deuterium incorporation is independent of the extent of reaction in the range of 20–40% conversion. The probability for excitation of uracil either by direct absorption or by sensitization is directly dependent upon the percent conversion.[8]

Uracil formation upon direct irradiation at 254 nm in 2-propanol solvent is partially quenched by piperylene. The Stern–Volmer plot shown in Figure 1 is concave, indicating reaction from both singlet and triplet states. Deuterium incorporation in uracil from irradiation in 2-propanol-*d* is completely quenched within experimental error by 0.033 M *cis*-piperylene (Table I). Quenching of excited BU from direct irradiation results in isomerization of both *cis*- and *trans*-piperylene. The Stern–Volmer plot indicates that the quantum yield of uracil formation from the singlet manifold is 1.3×10^{-2} and from the triplet manifold is 0.6×10^{-2}. These quantum yields are completely consistent with those predicted from the deuterium incorporation in uracil from direct irradiation of BU at 254 nm in 2-propanol-*d* solvent, assuming no kinetic isotope effect.[9] The Stern–Volmer plot indicates that the triplet lifetime for the reactive triplet state of BU is greater than 100 ns.[10]

The UV absorption spectrum of 5-bromouracil in 2-propanol solvent shows a weak shoulder at 300 nm (ϵ 338) on the intense absorption at 276 nm (ϵ 7640). We have tentatively assigned the band at 300 nm to the n–π^* transition and the band at 276 nm to the π–π^* transition. Direct irradiation of the n–π^* band of BU at 290 ± 20 nm results in an order of magnitude reduction in the quantum yield of uracil formation.[11] Furthermore, direct irradiation of BU plus 6×10^{-3} M *cis*-piperylene at 290 ± 20 nm yields little or no isomerization of the piperylene. These observations indicate that population of the π,π^* state is necessary for singlet reactivity and intersystem crossing to the reactive triplet state. A wavelength dependence of the intersystem crossing efficiency of thymine[12] and pyrimidine nucleosides[13] has been noted

---

(6) Reference 5 reports the quantum yield of uracil formation from irradiation of BU in 2-propanol solvent as 1.5×10^{-2}. The difference may reflect experimental error and/or differences in the percent conversion.

(7) Leonov, D.; Salomon, J.; Sasson, S.; Elad, D. *Photochem. Photobiol.* **1973**, *17*, 465.

(8) An example of a photosensitized reaction of cyclohexene with hydrogen chloride has been described by Arnold and Wong: Arnold, D. R.; Wong, P. C. *J. Am. Chem. Soc.* **1977**, *99*, 3361.

(9) The referees have suggested that *cis*-piperylene might possibly be serving as a quencher by trapping hydrogen bromide or bromine atom. Evidence against this possibility include isomerization of *trans*-piperylene to *cis*-piperylene, no observed participation of hydrogen bromide, and the internal consistency of the quenching data with the deuterium incorporation data.

(10) The minimum value for the lifetime of the reactive triplet state was calculated from the slope of the Stern–Volmer plot at low *cis*-piperylene concentrations and the assumption that quenching occurs at the diffusion controlled rate of 6.7×10^9 M^{-1} s^{-1} at 35 °C. The rate of diffusion was calculated as described by Osborne and Porter: Osborne, A. D.; Porter, G. *Proc. R. Soc. London, Ser. A* **1965**, *284*, 9.

(11) A similar wavelength dependence has been noted by Schulte-Frohlinde and co-workers.[5] The effect was explained in terms of competition of the rate-determining step for U formation with relaxation processes of the excited state.

(12) Kleopfer, R.; Morrison, H. *J. Am. Chem. Soc.* **1977**, *94*, 255.

Scheme I

$$\mathrm{BU} + h\nu\ (254\ \mathrm{nm}) \rightarrow {}^1\mathrm{BU}^*\ (\pi,\pi^*)$$

$${}^1\mathrm{BU}^*\ (\pi,\pi^*) \rightarrow \mathrm{BU},\ \phi = 0.96$$

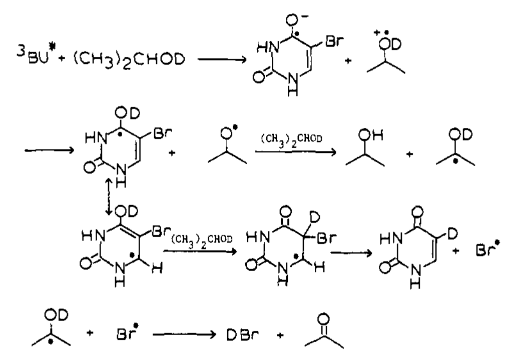
$${}^1\mathrm{BU}^*\ (\pi,\pi^*) \xrightarrow{\text{2-propanol}} \mathrm{U},\ \phi = 0.013$$

$${}^1\mathrm{BU}^*\ (\pi,\pi^*) \rightarrow {}^3\mathrm{BU}^*,\ \phi = 0.03$$

$${}^3\mathrm{BU}^* \xrightarrow{\text{2-propanol}} \mathrm{U},\ \phi = 0.20$$

$${}^3\mathrm{BU}^* \rightarrow \mathrm{BU},\ \phi = 0.80$$

Scheme II



and may also be due to the population of upper excited states.

A kinetic mechanism with quantum yields for the photoreduction of bromouracil to uracil is shown in Scheme I. The efficiency assigned to intersystem crossing of BU in the π,π^* singlet state was calculated as 0.03, assuming that energy transfer from triplet acetone occurs with unit efficiency as suggested by the data in Table II.

Deuterium incorporation in the 5 position of uracil as a function of the position of deuterium in 2-propanol suggests the following: (1) In the π,π^* singlet state BU reacts via homolysis of the vinyl carbon–bromine bond and the resulting vinyl radical is moderately selective in hydrogen atom abstraction. (2) In the reactive triplet state BU undergoes an ionic reaction with 2-propanol most likely via electron transfer. A reasonable mechanism for formation of uracil via initial electron transfer from 2-propanol to triplet BU is shown in Scheme II. The mechanism finds precedent in the photooxidation of alcohols with one-electron photooxidizing agents.[14] Reactivity of BU in the triplet manifold is dramatically sensitive to the oxidation potential or ionization potential of the solvent. Acetone-sensitized irradiation of BU in ethanol solvent leads to no reaction. The ionization potential of 2-propanol is less than the ionization potential of ethanol by 0.35 eV.[15]

The electron-transfer mechanism for the reaction of triplet BU with 2-propanol is analogous to that proposed by Ito, Saito, and Matsuura to explain the acetone-sensitized coupling of BU to tryptophan derivatives.[4] We note, however, that our results suggest that some amino acid residues less easily oxidized than tryptophan or cysteine should be reactive with triplet BU but that intimate association may be required to achieve reasonable efficiency.

Acknowledgment. We thank Professor Harry Morrison for a helpful discussion. Support of this research by Grant GM24965 from the General Medical Institute and from HEW's Biomedical Research Support Grant to the University of Colorado at Boulder is gratefully acknowledged. We also thank the Colorado State University Regional NMR Center, funded by NSF Grant CHE 78-18581, and Martin Ashley for technical assistance with the NMR measurements.

---

(13) Salet, C.; Bensasson, R.; Becker, R. S. *Photochem. Photobiol.* **1979**, *30*, 325.

(14) Ledwith, A.; Russell, P. J.; Sutcliffe, L. H. *Proc. R. Soc. London, Ser. A* **1973**, *332*, 151.

(15) Watanabe, K. *J. Chem. Phys.* **1957**, *26*, 542.

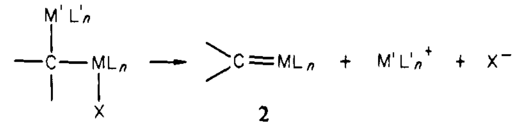
1,1-Dimetalloalkenes Containing Aluminum as Well as Titanium or Zirconium. Their Structures and Use as Novel Alkenylidene and Alkenyl Transfer Agents[1]

Tadao Yoshida and Ei-ichi Negishi*

Department of Chemistry, Purdue University
West Lafayette, Indiana 47907

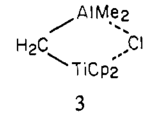
Received September 15, 1980

Although β elimination is one of the most commonly employed methods for the formation of the carbon-to-carbon double bond, it has not been adequately developed as a route to metal-containing double bond, i.e., metal–carbene complexes.[2] Conceptually, 1,1-dimetallo derivatives represented by **1** could undergo spontaneous or assisted syn or anti β elimination to metal–carbene complexes (**2**). Indeed, it has recently been reported that **3** undergoes a facile olefination reaction of carbonyl compounds and that the results can be interpreted in terms of the intermediacy of an aluminum-stabilized metal–carbene species **4**.[3]

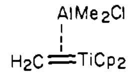


(1)

1 **2**



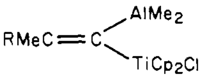
3



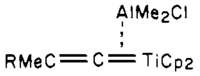
4

Cp = η^5-C_5H_5

We have previously synthesized 1,1-dimetalloalkenes (**5**) by the reaction of 1-alkynyldimethylalanes with the Me_3Al–Cl_2TiCp_2 reagent system.[4] Attractive possibilities of probing the potential significance of hypothetical metal–carbene species **6** through investigation of the stereochemistry of **5** as well as of developing novel alkenylidene transfer agents prompted us to undertake a detailed investigation of **5**.



5a, R = *n*-Pent
b, R = *n*-Pr



6

As briefly described earlier,[4] the reaction of 1-heptynyldimethylalane with an equimolar amount of an apparently homogeneous 1:1 mixture of Me_3Al and Cl_2TiCp_2 in methylene chloride at room temperature produces **5a** in excellent yield (90–100%), as judged by ^{1}H NMR as well as GLC analysis of the hydrolysis products. Since 2-octenes are not produced in any more than 1% yield, the reaction is ≥99% regioselective. The presence of two metal groups in the terminal position was also indicated by the formation of >95% pure 1,1-dideuterio-2-methylheptene in 85–95% yield on deuterolysis of **5a** with D_2O. Our attempts to selectively remove Me_2AlCl formed as a byproduct through evaporation did not succeed. However, the use of preformed $Cl(Me)TiCp_2$ prepared by the method of Clauss and Bestian[5] readily solved this problem. Under these conditions the carbo-

---

[1] Selective Carbon–Carbon Bond Formation via Transition Metal Catalysis. 17. Controlled Carbometalation. 8. Part 7: Kobayashi, M.; Negishi, E. *J. Org. Chem.* **1980**, *45*, 5223.

[2] For a review, see: Casey, C. P. *J. Organomet. Chem. Libr.* **1976**, *1*, 397–421.

[3] (a) Tebbe, F. N.; Parshall, G. W.; Reddy, G. S. *J. Am. Chem. Soc.* **1978**, *100*, 3611–3613. (b) Pine, S. H.; Zahler, R.; Evans, D. A.; Grubbs, R. H. *J. Am. Chem. Soc.* **1980**, *102*, 3270–3272. (c) See also: Tebbe, F. N.; Parshall, G. W.; Ovenall, D. W. *Ibid.* **1979**, *101*, 5074–5075.

[4] Van Horn, D. E.; Valente, L. F.; Idacavage, M. J.; Negishi, E. *J. Organomet. Chem.* **1978**, *156*, C20–C24.

[5] Clauss, K.; Bestian, H. *Liebigs Ann. Chem.* **1962**, *654*, 8–19.

0002-7863/81/1503-1276$01.25/0