P′ planes. The boron–phosphorus distance is 1.852 (9) Å, close to that seen in similar monomeric organophosphinoboranes.[8] The angles at the B and P centers do not deviate more than 1.7° from the regular trigonal values. The boron–carbon distances are similar to those in other boron mesityl species.[9] The phosphorus–carbon bond is not particularly short although there appears to be few trivalent phosphorus adamantyl derivatives available for comparison.

The major structural features of interest in **1** concern (a) the short P–P′ bond length, (b) the planarity of the phosphorus centers, and (c) the large twist angle between the phosphorus planes. Point (c) tends to discredit the analogy between **1** and butadiene which might have accounted for some of the observed shortening in the P–P′ bond in terms of orbital interactions between the π-orbital systems of the B–P bonds. It is notable that the B–P bond still has considerable multiple character[10] as indicated by the B–P distance of 1.852 (9) Å, although the dihedral angle between the B and P planes is somewhat larger (presumably for steric reasons) than those previously observed. The planar nature of the phosphorus and the short B–P bond indicates that there is significant lone pair interaction with the empty p-orbital on boron.

Regarding point (b), the nearly regular trigonal-planar angles at phosphorus indicate that hybridization is close to sp^2. Thus, **1** differs from normal diphosphanes which often display angles at phosphorus that are much less than tetrahedral, indicating reduced s-character (significantly less than sp^3) in the bonding orbitals. These differences in bond angles point to sp^2–sp^2 orbital overlap for the P–P′ bond in **1** instead of overlap between orbitals with substantially more p (and less s) character as in "normal" diphosphanes. Such differences in hybridization are thought to cause significant variation in C–C bond lengths in hydrocarbons.[2] It seems reasonable to assume that the greater hybridization differences in phosphorus compounds could give rise to larger variation in P–P bonds.

In connection with point (a) it could be argued that the short P–P′ bond arises from a reduction in phosphorus lone pair–lone pair repulsion as a result of the interaction with the empty boron p-orbital. Interelectronic repulsion is probably reduced, but calculations and experimental data on *cis*- and *trans*-diphosphenes give almost identical P–P distances which suggest that the repulsions play a minor role. The phosphorus–phosphorus bond length in **1**, 2.109 (4) Å, which is the shortest P–P single bond reported to date,[11] is marginally closer to the average length of a P–P double bond than to that of a single bond. For example, the first P–P double bond to be structurally characterized[3] had a length of 2.034 (2) Å, whereas P–P single bonds are about 2.22 Å long.[12] Nonetheless, the P–P bond in **1**, owing to the structural configuration of the molecule, must be regarded as a single bond as it involves only one orbital from each phosphorus. Further evidence for this assignment comes from the ^{31}P NMR spectra of **1** and **2** that show singlets at 2.8 and −22.3 ppm. These values are far from those seen in the doubly bonded compounds which generally appear several hundred ppm downfield.[4] Instead, they are much closer to the shifts for normal diphosphanes which often appear at δ values between 0 and −100 ppm.[13]

In summary, it appears that the answer to the title question is that the shortening in diphosphenes is about equally divided between p–p π-overlap and rehybridization of the σ-orbitals. Calculations on the hypothetical species *trans*-HPPH seem to bear out these experimental data.[4] The most recent[14] showed that the bonding π-orbital in this species (which is the HOMO) appears at an energy of 9.69 eV below the LUMO, whereas the stabilization of the σ(PP) bond is 25.02 eV. In addition, estimates of the rotational barrier in diphosphenes vary from 20 to 35 kcal mol^{-1},[4,14,15] whereas the strength of the π-bonds in alkenes is in the 50–60 kcal mol^{-1} [16] range which is in good agreement with the respective proportions of contraction due to p–p π-overlap. Other support comes from calculations[17] on the hypothetical diphosphene transition-metal complex, $H_2P_2Cr(CO)_5$, that indicate a large amount (0.3 electrons) of back-donation by the metal fragment into the b_g (π^*-type) orbital of the ligand. However, this extensive transfer of electron density into the ligand antibonding orbital results in only slight lenghtening of the P–P bond upon complexation. This result, which is in agreement with structural and spectroscopic studies, is consistent with weaker p–p orbital interactions.[4,18]

Acknowledgment. We thank the National Science Foundation (CHE-8618739) for financial support.

Supplementary Material Available: Tables of crystallographic data, summary of data collection and refinement, bond distances and angles, anisotropic thermal parameters and hydrogen coordinates (8 pages); table of observed and calculated structure factors (7 pages). Ordering information is given on any current masthead page.

(8) Feng, X.; Olmstead, M. M.; Power, P. P. *Inorg. Chem.* **1986**, *25*, 4615. B–P distance = 1.859 (3) Å.

(9) The structures of numerous compounds involving the $-BMes_2$ and related groups bonded to phosphorus have appeared in the literature. See ref 8 and Bartlett, R. A.; Feng, X.; Power, P. P. *J. Am. Chem. Soc.* **1986**, *108*, 6817. Olmstead, M. M.; Power, P. P.; Weese, K. J.; Doedens, R. J. *J. Am. Chem. Soc.* **1987**, *109*, 2541. Bartlett, R. A.; Feng, X.; Olmstead, M. M.; Power, P. P.; Weese, K. J. *J. Am. Chem. Soc.* **1987**, *109*, 4851.

(10) Bartlett, R. A.; Dias, H. V. R.; Feng, X.; Power, P. P. *J. Am. Chem. Soc.* **1989**, *111*, 1306 and references therein.

(11) Niecke, E.; Rüger; Krebs, A. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 544. Binger, P.; Biedenbach, B.; Krüger, C.; Regitz, M. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 764. Barron, A. R.; Cowley, A. H.; Hall, S. W.; Nunn, C. M. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 837. These publications also feature short P–P distances of 2.129 Å, 2.147 (1) Å and 2.118 (3) Å as part of the highly strained cage compounds. Calculations have accounted for this phenomenon in terms of olefinic character. See: Schoeller, W. W.; Staemmler, V.; Rademacher, P.; Niecke, E. *Inorg. Chem.* **1984**, *25*, 4382.

(12) Corbridge, D. E. *The Structural Chemistry of Phosphorus*; Elsevier: Amsterdam, 1976; p 393.

(13) Mark, V.; Dungan, C. H.; Crutchfield, M. M.; van Wazer, J. R. *Topics in Phosphorus Chemistry*; Grayson, M., Griffith, E. J., Eds.; Wiley: New York, 1967; Vol. 5, Chapter 4.

(14) Allen, T. L.; Scheiner, A. C.; Yamaguchi, Y.; Schaefer, H. F., III *J. Am. Chem. Soc.* **1986**, *108*, 7579. These and earlier calculations also indicate that lone-pair/lone-pair repulsions probably play only a minor role in the determination of the P–P bond length. For example, there are only small differences in the P–P distance of the cis and trans isomers of HPPH.

(15) Cominade, A.-M.; Verrier, M.; Ades, C.; Paillous, N.; Koenig, M. *J. Chem. Soc., Chem. Commun.* **1984**, 875.

(16) Miller, S. I. *J. Chem. Educ.* **1978**, *55*, 778.

(17) Schugart, K. A.; Fenske, R. F. *J. Am. Chem. Soc.* **1985**, *107*, 3384.

(18) Bartlett, R. A.; Dias, H. V. R.; Power, P. P. *J. Organomet. Chem.* **1989**, *362*, 87 and references therein.

Exclusive Abstraction of Nonexchangeable Hydrogens from DNA by Calicheamicin $\gamma 1^I$

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The calicheamicins[1] are potent antitumor antibiotics that are believed to mediate their DNA damaging properties and cytotoxicity primarily via oxidative strand scission.[2] In vitro calicheamicin $\gamma 1^I$ (**1**), in the presence of thiols, produces double strand cuts in supercoiled, covalently closed circular DNA, in DNA restriction fragments, and in synthetic oligomers with a high degree of sequence specificity.[2,3] It has been proposed that DNA scission

(1) (a) Lee, M. D.; Dunne, T. S.; Siegel, M. M.; Chang, C. C.; Morton, G. O.; Borders, D. B. *J. Am. Chem. Soc.* **1987**, *109*, 3464. (b) Lee, M. D.; Dunne, T. S.; Chang, C. C.; Ellestad, G. A.; Siegel, M. M.; Morton, G. O.; McGahren, W. J.; Borders, D. B. *J. Am. Chem. Soc.* **1987**, *109*, 3466.

(2) Zein, N.; Sinha, A. M.; McGahren, W. J.; Ellestad, G. A. *Science* **1988**, *240*, 1198.

(3) Zein, N.; Poncin, M.; Nilakantan, R.; Ellestad, G. A. *Science* **1989**, *244*, 697.

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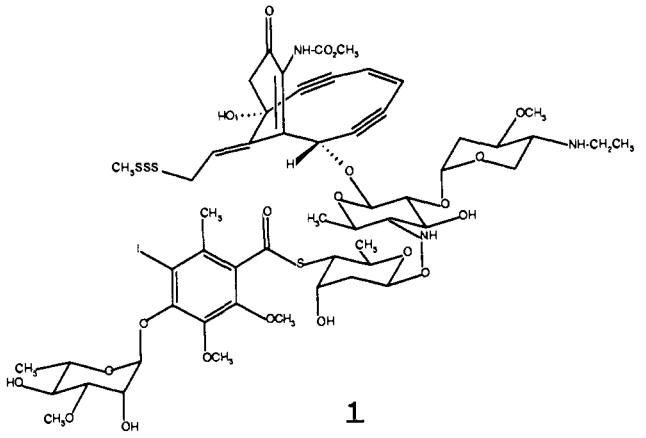
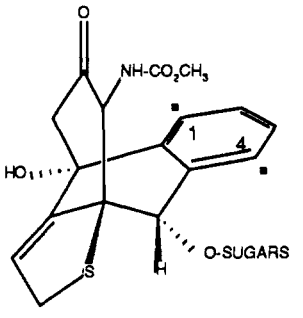
occurs as follows: In an initial step, calicheamicin $\gamma 1^1$ (**1**) asso-



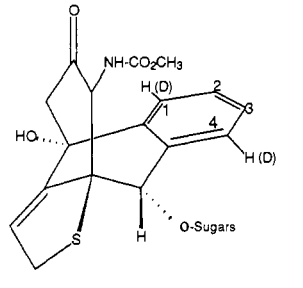
1

ciates with the DNA in the minor groove and subsequent thiol-mediated reduction of the labile methyl trisulfide grouping triggers the generation of the 1,4-dehydrobenzene diradical species, **2**. Intermediate **2** then initiates strand scission by hydrogen abstraction from the DNA deoxyribose rings yielding the inactivated calicheamicin species, **3**.[3]



2

This proposed scheme implies a certain association between calicheamicin $\gamma 1^1$ and DNA with the diynene moiety partially inserted between the two strands in the minor groove. Moreover, this proposal suggests that under these circumstances, a molecule of the diradical intermediate **2** is more likely to abstract hydrogens from the DNA rather than from the thiol/solvent system to yield **3**. Two questions of major interest are then (i) in the presence



3

of bulk DNA, what ratio of the hydrogens abstracted by **2** comes from the DNA versus the thiol/solvent system and (ii) are both hydrogens abstracted from the same source (which would translate in the case of DNA into double-stranded cuts). In this report, we present direct evidence that in the presence of DNA both hydrogens are almost exclusively abstracted from the DNA. In addition, these experiments confirm that the carbon sites which abstract the hydrogens from the DNA are C_1 and C_4 in **2** as proposed.[4a]

(4) (a) For a recent study on neocarzinostation, see: Chin, D.-H.; Zeng, C.-H.; Costello, E. E.; Goldberg, I. H. *Biochemistry* **1988**, *27*, 8106. (b) This is in contrast to the observations observed by Chin et al. with neocarzinostatin. See above ref 4a.

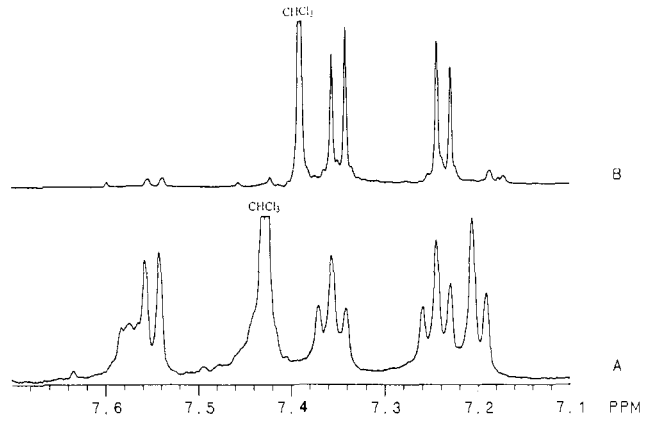


Figure 1.

In one experiment, calicheamicin $\gamma 1^I$ (**1**) (0.36 mM) was treated with deuterated methylthioglycolate,[5] $DSCH_2COOCH_3$ (50 mM), in the presence of sonicated calf thymus DNA[6] (ca. 3 mM in base pairs; repeatedly dissolved in D_2O and lyophilized[7]) in 10% C_2D_5OD in Tris/DCl/D_2O at pD 7.8[8] for 3 h at 37 °C. Preparative TLC[9] was used to isolate **3** in 65% yield. The ^1H NMR spectrum[10] of the product (aromatic portion shown in Figure 1A)[11] contained doublets at δ 7.20 and 7.55 ppm, peaks previously assigned to H_4 and H_1, respectively, and triplets at δ 7.24 and 7.36 ppm (assigned to H_3 and H_2, respectively).[1] The relative integrated intensities and spin–spin coupling patterns in this spectrum were identical with those obtained when compound **3** was prepared from the reaction of calicheamicin in a protonated thiol solvent mixture in the absence of DNA. This result indicates that no deuterium incorporation at C_1 or C_4 occurred. Moreover, incorporation of hydrogens on both carbons implies that DNA is the sole source of both protons for the formation of **3**.

To further support this conclusion, **1** was treated under identical conditions to those described above except that DNA was omitted from the deuterated reaction mixture. Under these conditions, **3** was produced in approximately 20% yield. The proton NMR spectrum of this compound showed over 98% deuterium incorporation at carbons 1 and 4 (Figure 1B). The only differences between the two spectra (1A and 1B) appear in the aromatic region. The peaks at δ 7.20 (H_4) and 7.55 ppm (H_1) are essentially absent, and the triplets ordinarily seen at δ 7.24 (H_3) and 7.36 (H_2) ppm collapsed to sharp doublets centered at δ 7.24 and 7.35 ppm. This shows that for these reaction conditions, incorporated deuterium almost certainly comes from the mercapto deuterium of the methylthioglycolate.[4b]

The exclusion of deuterium incorporation in **3** in the reaction performed in the presence of DNA indicates an intimate association of the drug with DNA followed by abstraction of non-exchangeable hydrogens from the DNA. These results represent the first chemical evidence that both hydrogens must be extracted from both DNA strands since monodeuterated products were not observed. Furthermore, these studies show that calicheamicin does in fact abstract nonexchangeable hydrogens from the DNA to

(5) Hensens, O. D.; Dewey, R. S.; Liesch, J. M.; Napier, M. A.; Reamer, R. A.; Smith, J. L.; Albers-Schonberg, G.; Goldberg, I. H. *Biochem. Biophys. Res. Commun.* **1983**, *113*, No. 2, 538.

(6) Maniatis, T.; Fritsch, E. D.; Sambrook, J. *Molecular Cloning: A Laboratory Manual*; Cold Spring Harbor Laboratory: Cold Spring Harbor, NY, 1982; p 480.

(7) Wuthrich, K. *NMR of Proteins and Nucleic Acids*; John Wiley and Sons: New York, 1986; p 37.

(8) pD = pH meter reading +0.40: Glasoe, P. K.; Long, F. A. *J. Phys. Chem.* **1960**, *64*, 188.

(9) TLC conditions: preparative thick-layer silica gel plates with 90:10 ethyl acetate saturated with 0.2 M KH_2PO_4: isopropyl alcohol as eluting solvent.

(10) ^1H NMR experiments were carried out on a GE GN500 at 500.11 mHz. Samples were dissolved in $CDCl_3$ with six drops of CD_3OD added to aid solution. A spectral width of −0.5 to 10 ppm was used.

(11) The unidentified peaks centered at δ 7.58 ppm could be due to DNA degradation products from the reaction of DNA with calicheamicin $\gamma 1^1$.

initiate strand scission. The high yields of **3** obtained in the presence of DNA are in agreement with the belief that DNA promotes or acts as a template for the reactions of small molecules.[12] Thus the two strands of the DNA confine the diynene moiety in the minor groove in a manner that facilitates the aromatization of this moiety.

(12) Sundquist, W. I.; Bancroft, D. P.; Chassot, L.; Lippard, S. J. *J. Am. Chem. Soc.* **1988**, *110*, 8559.

Synthesis of Heteronuclear Metal-Allenyl Clusters: Transition-Metal-Propargyl Compounds as Templates for the Construction of Mixed Metal-Metal Bonds

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Heteronuclear metal clusters represent an important and rapidly growing class of compounds.[1] The presence of different metal centers in the same molecule can provide useful information concerning the activation of hydrocarbon substrates in stoichiometric and catalytic reactions. So far, however, synthetic methodology for this class of compounds is, in general, not well developed.[2] We now report a new, facile one-step preparation of heteronuclear metal complexes containing bridging allenyl ligands; these compounds had been essentially unknown for mixed metal systems.[3] Our method appears to be general and may be applicable to compounds with related bridging hydrocarbon groups. The heteronuclear μ-allenyl compounds described herein may be expected to undergo unusual transformations based on reactivity studies of homonuclear μ-allenyl compounds.[4]

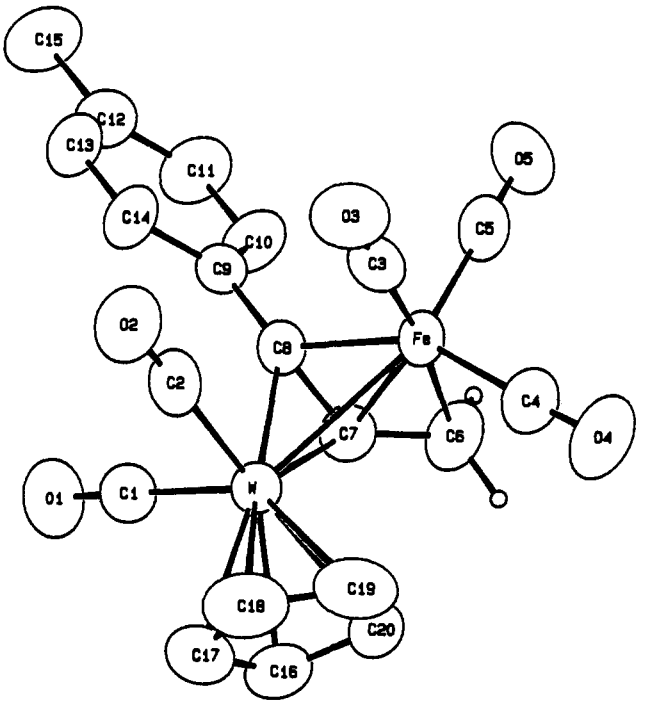


Figure 1. ORTEP plot of **2e** showing atom numbering scheme. Only the CH_2 hydrogens are shown, drawn at an arbitrary radius. Non-hydrogen atoms are drawn at the 50% probability level.

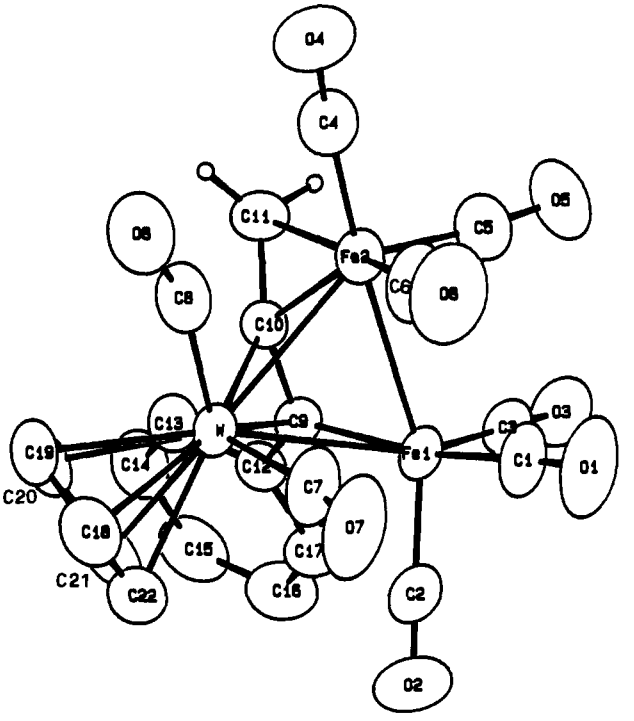
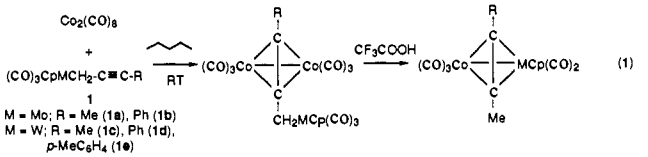


Figure 2. ORTEP plot of **3d** showing atom numbering scheme (drawn as described in Figure 1).

We recently used the alkyne functionality of transition-metal-propargyl compounds as a template for the two-step synthesis of the heteronuclear μ-alkyne complexes $(CO)_3Co(\mu\text{-}RC{\equiv}CMe)MCp(CO)_2$[5] (eq 1). An extension of the chemistry



†To whom inquiries concerning the X-ray crystallographic work should be addressed.

(1) General reviews: (a) Roberts, D. A.; Geoffroy, G. L. In *Comprehensive* Organometallic *Chemistry*; Wilkinson, G., Stone, F. G. A., Abels, E. W., Eds.; Pergamon Press: Oxford, U.K., 1982; Chapter 40. (b) Geoffroy, G. L. In *Metal Clusters in Catalysis*; Gates, B. C., Guczi, L., Knozinger, H., Eds.; Elsevier: New York, 1986; Chapter 1. (c) Vargas, M. D.; Nicholls, J. N. *Adv. Inorg. Chem. Radiochem.* **1987**, *30*, 123. (d) Vahrenkamp, H. *Adv. Organomet. Chem.* **1983**, *22*, 169.

(2) Selected examples: (a) Stone, F. G. A.; Williams, M. L. *J. Chem. Soc., Dalton Trans.* **1988**, 2467, and cited papers by Stone et al. (b) Lukehart, C. M.; True, W. R. *Organometallics* **1988**, *7*, 2387. (c) Aime, S.; Milone, L.; Osella, D.; Tiripicchio, A.; Lanfredi, A. M. M. *Inorg. Chem.* **1982**, *21*, 505. (d) Jaouen, G.; Marinetti, A.; Mentzen, B.; Mutin, R.; Saillard, J.-Y.; Sayer, B. G.; McGlinchey, M. J. *Organometallics* **1982**, *1*, 753. (e) Jensen, S. D.; Robinson, B. H.; Simpson, J. *Organometallics* **1986**, *5*, 1690. (f) Alvarez-Toledano, C.; Parlier, A.; Rose-Munch, F.; Rudler, H.; Daran, J. C.; Knobler, C.; Jeannin, Y. *J. Organomet. Chem.* **1987**, *323*, 371. (g) Chetcuti, M. J.; Green, K. A. *Organometallics* **1988**, *7*, 2450.

(3) Exceptions are $PPh_4[Fe_3Rh_2(CO)_{10}(\mu\text{-}CO)_3(\mu_4\text{-}\eta^3\text{-}MeC{=}C{=}CH_2)]$ (Attali, S.; Dahan, F.; Mathieu, R. *Organometallics* **1986**, *5*, 1376) and $FeCo(CO)_5L(\mu\text{-}\eta^3\text{-}R'C{=}C{=}CR_2)$ (L = CO, PPh_3; $R_2 = H_2$, HMe, Me_2; R' = Me, Et, CH_2OH) (Aime, S.; Osella, D.; Milone, L.; Tiripicchio, A. *Polyhedron* **1983**, *2*, 77); however, the FeCo complexes could not be accurately characterized by X-ray crystallography.

(4) (a) Nucciarone, D.; Taylor, N. J.; Carty, A. J. *Organometallics* **1988**, *7*, 127. (b) Nucciarone, D.; Taylor, N. J.; Carty, A. J.; Tiripicchio, A.; Tiripicchio, M. T.; Sappa, E. *Organometallics* **1988**, *7*, 118. (c) Nucciarone, D.; MacLaughlin, S. A.; Taylor, N. J.; Carty, A. J. *Organometallics* **1988**, *7*, 106. (d) Randall, S. M.; Taylor, N. J.; Carty, A. J.; Haddah, T. B.; Dixneuf, P. H. *J. Chem. Soc., Chem. Commun.* **1988**, 870.

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