Experimental support for the above conclusions was obtained by measurements of the magnetic susceptibility of **3** in the temperature interval 65–300 K. The effective magnetic moment of **3** increased with temperature, consistent with strong antiferromagnetic coupling.[18] At room temperature, μ_{eff} reached a value of only 2.1 μ_B, which may be compared to the μ_{eff} of 3.5 μ_B for **1** at the same temperature.[3e] The close approach of the two metal atoms in **3** apparently leads to a significant splitting of the d orbitals and enforces spin pairing. We conclude that **3** exhibits an exceptional case of metal–metal bonding between two octahedral Cr(III) ions.

Acknowledgment. We thank Dr. C. Z. Ni for help with the structure determination and R. A. Heintz for some experiments. This research was supported by the National Science Foundation (CHE 8820354) and by the Deutscher Akademischer Austauschdienst (NATO postdoctoral fellowship to C.J.).

Supplementary Material Available: X-ray structure determination summary and tables of atomic coordinates and equivalent isotropic displacement coefficients, bond lengths and angles, anisotropic displacement coefficients, and hydrogen atom coordinates and isotropic displacement coefficients for **3** (6 pages). Ordering information is given on any current masthead page.

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Uses of Metallacyclobutenes in Heterocyclic Synthesis. Synthesis and Structural Characterization of 1,2-Dihydrophosphetes

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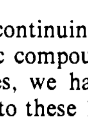
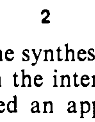
In contrast to the wealth of chemistry reported for many small-ring heterocyclic compounds, there is a surprising dearth of information on the 1,2-dihydrophosphete ring system (structure **1**). Though a transition-metal complex of a 1,2-dihydrophosphete was recently reported,[2] in no case has a simple 1,2-dihydrophosphete been isolated; existing reports are of the corresponding 1-oxides (structure **2**).[3-5]



1



2

As part of a continuing study of the synthesis of carbocyclic and heterocyclic compounds through the intermediacy of metallacyclobutenes, we have discovered an apparently general synthetic route to these 1,2-dihydrophosphete heterocycles. A variety of substituents may be introduced, and the heterocycles may be readily isolated in good yield as the unoxidized dihydrophosphetes (structure **1**).

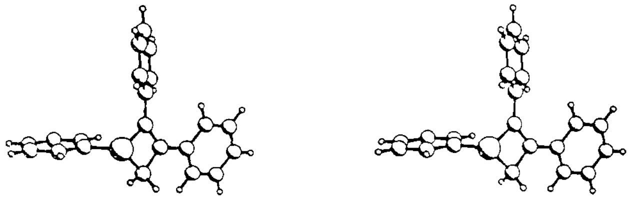
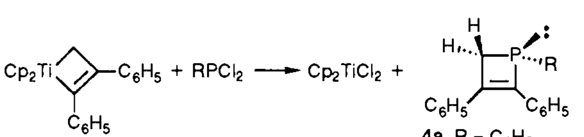


Figure 1. Stereoscopic view of 1,2-dihydrophosphete **4a**. Bond lengths[12] (Å): P(1)–C(2), 1.821 (3); P(1)–C(4), 1.886 (4); C(2)–C(3), 1.366 (5); C(3)–C(4), 1.517 (5); P(1)–C(11), 1.842 (3); C(2)–C(21), 1.477 (4); C(3)–C(31), 1.480 (4). Bond angles (deg): C(4)–P(1)–C(11), 104.7 (1); C(2)–P(1)–C(4), 74.0 (2); C(2)–P(1)–C(11), 104.3 (1); P(1)–C(2)–C(3), 95.5 (2); P(1)–C(2)–C(21), 128.6 (2); C(3)–C(2)–C(21), 135.8 (3); C(2)–C(3)–C(4), 101.3 (3); C(2)–C(3)–C(31), 134.3 (3); C(4)–C(3)–C(31), 124.3 (3); P(1)–C(4)–C(3), 88.0 (2).

When the diphenyltitanacyclobutene **3**[6] is treated with 1 equiv of phenyldichlorophosphine in benzene solution at room temperature, titanocene dichloride immediately precipitates in nearly quantitative yield as a red microcrystalline solid.[7] Filtration under nitrogen of the reaction mixture through a short column of silica, eluting with deoxygenated diethyl ether, followed by evaporation of solvents in vacuo, affords the dihydrophosphete **4a** as a white solid in 66% yield.[8]



3

4a, R = C_6H_5
b, R = CH_3CH_2
c, R = $(CH_3)_3C$
d, R = CH_3CH_2O

The dihydrophosphete **4a** (and its congeners; vide infra) is most readily characterized by its ^{1}H NMR spectrum. The two protons of the methylene group are stereochemically inequivalent and, at moderate field (360 MHz), are sufficiently well resolved to give rise to a simple first-order pattern of two doublets of doublets ($J_{\text{H-H}}$ = 14.4 Hz, $J_{\text{P-H}}$ = 9.6, 4.2 Hz).

Single crystals of **4a** were obtained from a cooled toluene/pentane solution. X-ray crystallographic analysis of **4a** proceeded routinely.[9] A stereoscopic view of the structure of **4a** is provided in Figure 1. The phosphacyclobutene ring is roughly planar, with an average deviation from planarity of 0.05 Å. The C–P–C bond angle of 74.0° is identical with that reported by Mathey[2] for the tungsten pentacarbonyl complex of a related 1,2-dihydrophosphete, as is the sp^3 C–sp^2 C bond length of 1.517 Å. The C=C double bond is somewhat longer than in the Mathey compound, at 1.366 Å (compared to 1.331 Å), while the sp^3 C–P bond is somewhat shorter, at 1.886 Å (compared to 1.902 Å). Other relevant bond lengths and angles are presented in the caption to Figure 1. In short, **4a** displays a ground-state structure quite consistent with simple formulation as the 1,2-dihydrophosphete. Though partial contribution of the ring-opened phosphabutadiene structure has been invoked to account for the structure of the tungsten pentacarbonyl complex of a 1,2-dihydrophosphete,[2] it does not appear necessary to invoke participation of the phosphabutadiene structure

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(1) Address correspondence to this author at the University of Oregon, Department of Chemistry, Eugene, Oregon 97403.

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(8) Full characterization of **4a–d**, as well as experimental details for the preparation of **4a**, are provided in the supplementary material.

(9) Crystal data: $C_{21}H_{17}P$, M = 300.343, monoclinic, space group $P2_1/n$, a = 9.265 (4) Å, b = 6.863 (3) Å, c = 26.082 (11) Å, β = 93.826 (11)°, V = 1655 Å^3, Z = 4, D_{calcd} = 1.2 g cm^{-3}. Atoms were located by direct methods. Least-squares refinement converged to an R value of 0.050 for 1471 reflections [$I > 3\sigma(I)$]. Crystallographic data are provided in the supplementary material.

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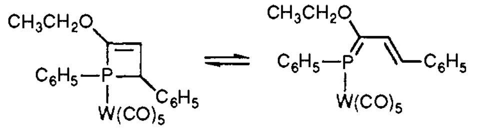
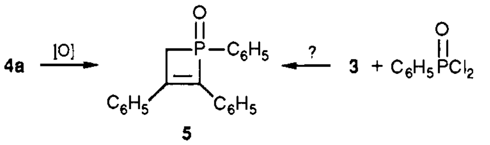
in determining the ground-state metrical parameters of the uncomplexed heterocycle, **4a**.



Although our first preparation of **4a**, in which workup was carried out in air rather than under nitrogen, gave **4a** contaminated with significant amounts of what appears to be the dihydrophosphete oxide,[10] **5**, we find that pure **4a** is remarkably inert toward oxidation. Solutions of **4a** in perdeuteriobenzene show only traces of the putative **5** after storage for several weeks under an atmosphere of pure oxygen. Attempted independent preparation of oxide **5** through the reaction of the titanacyclobutene **3** with phenyldichlorophosphine oxide gave inconclusive results.



The reaction of titanacyclobutene **3** with dichlorophosphines appears quite general.[8] Ethyldichlorophosphine gives dihydrophosphete **4b**, though **4b** appears unstable and has not yet been isolated or fully characterized. *tert*-Butyldichlorophosphine also reacts, though this reaction is considerably slower. Workup after 24 h affords the product, **4c**, in 30–50% yield. Ethyl phosphorodichloridite also reacts readily to produce the corresponding dihydrophosphete **4d**, as a stable white solid in 73% yield. In only one case have we failed to observe formation of the dihydrophosphete product. (Diisopropylamino)dichlorophosphine does not react with titanacycle **3** at room temperature; elevation of the temperature to ca. 50 °C results in decomposition.

We are currently extending this chemistry to titanacyclobutenes bearing substituents other than the phenyl groups present in **3** and are also exploring the use of other main-group electrophiles to remove the organic fragment from these titanacyclobutenes and other metallacyclic complexes prepared in our laboratories. The electrocyclic ring-opening of the 1,2-dihydrophosphetes is also being explored.[11]

Acknowledgment. This work was supported by the National Institutes of Health (Grant GM39494).

Registry No. 3, 74834-09-6; **4a**, 123751-84-8; **4b**, 123751-85-9; **4c**, 123751-86-0; **4d**, 123751-87-1; **5**, 123751-88-2; $C_6H_5PCl_2$, 644-97-3; $CH_3CH_2PCl_2$, 1498-40-4; $(CH_3)_3CPCl_2$, 25979-07-1; $CH_3CH_2OPCl_2$, 1498-42-6.

Supplementary Material Available: Details of the preparation of **4a**, spectral characterizations of **4a–d**, and crystallographic data tables for **4** (9 pages); tables of observed and calculated structure factors for **4a** (8 pages). Ordering information is given on any current masthead page.

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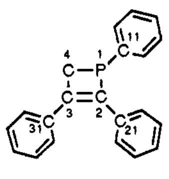
(10) ^{1}H NMR shows a new pair of dd at δ 3.38 and 3.43; MS displays the parent ion at m/z = 316.

(11) Electrocyclic ring-opening of a putative dihydrophosphete to a vinylphosphinidene has been postulated by Bestmann et al.: Bestmann, H. J.; Schmid, G.; Sandmeier, D. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 53–54. Mathey has reported similar reactivity for the $W(CO)_5$ complex of a dihydrophosphete: Tran Huy, N. H.; Mathey, F. *Tetrahedron Lett.* **1988**, *29*, 3077.

(12) Atom numbering scheme:



Design and Dynamics of a Chemically Triggered Reaction Cascade Leading to Biradical Formation at Subambient Temperature

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Mechanistic studies of the antitumor agents neocarzinostatin,[1] calichemicin,[2] and esperamicin[3] suggest, at a minimum, three common features essential to the operation of these antibiotics: (1) nondestructive high-affinity binding to DNA and (2) a chemical triggering mechanism leading to a high-energy intermediate capable of (3) rapid biradical formation at physiological temperatures. We describe herein the design, synthesis, and reactivity of a molecule that exhibits the latter two features and can be readily adapted to incorporate the first.[4]

Thiol **1** was envisioned to undergo a base-induced internal S_N2' displacement reaction to form the allenic sulfide **3** (Scheme I). This intermediate contains the (*Z*)-1,2,4-heptatrien-6-yne subunit, a functional group that has been shown to rearrange to the corresponding alkylbenzenediyl in the case of the parent substrate (*Z*)-1,2,4-heptatrien-6-yne (→α,3-dehydrotoluene, $t_{1/2} \sim 24$ h at 37 °C, eq 1).[5] In the latter study, it was demonstrated that substitution of methyl for hydrogen on the allenic terminus leads to a 6-fold enhancement in the rate of biradical formation.[5] To the extent that the sulfur atom of **4** provides additional stabilization of a radical intermediate, the hypothetical cyclization **3** → **4** was anticipated to be even more rapid. The synthesis of **1** and **2** and the dynamics of their transformation to **3** and **4** are described below.

(1)

(*Z*)-Ethyl 2,3-dibromopropenoate underwent selective replacement of the β-bromide upon treatment with (trimethylsilyl)acetylene (1.7 equiv), *N*,*N*-diisopropylethylamine (1.7 equiv), cuprous iodide (0.20 equiv), and tetrakis(triphenylphosphine)palladium (0.05 equiv) in *N*,*N*-dimethylformamide at 0 °C for 10 h, to produce the (*Z*)-bromo ester **5** in 90% yield.[6] Reduction of the ester group of **5** with diisobutylaluminum hydride (2.3 equiv) in toluene at −78 °C for 30 min and at 0 °C for 30 min formed the corresponding alcohol (94%), which was protected as its *tert*-butyldiphenylsilyl ether derivative [*tert*-butyldiphenylsilyl chloride (1.2 equiv), 4-(dimethylamino)pyridine (DMAP, 0.27 equiv), and triethylamine (5 equiv) in methylene chloride at 23 °C for 3.5 h, 95%]. Slow addition of bromide **6** to a solution of *tert*-butyllithium (2.5 equiv, 0.14 M) in tetrahydrofuran–ether–

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