the Fermi level was noted in either case, suggesting that metallic rhodium was not formed on either deposition or subsequent hydrogenation procedures. Other changes in the UP spectrum (Figure 1E) are also observed. The emission attributed to allyl ligand electrons at 10.8 eV is greatly reduced, as expected for formation of the hydride complex from the diallylrhodium species. The peak near the Fermi level has broadened as compared with the spectrum for the deposited diallyl species. The feature at 5.2 eV remains unchanged throughout the various chemical changes, and this band is assigned to nonbonding oxygen (2p) electrons.[17]

In the experiments described above, the UPS technique has been used to observe changes in electron density at oxygen effected by the formation of new chemical surface species made according to reaction schemes developed under "normal" conditions. This represents the first use of UHV techniques to directly probe bonding changes in a catalytically active transition-metal complex supported on a single-crystal oxide under conditions which approximate actual catalysis.

Acknowledgment. We gratefully acknowledge the National Science Foundation and the Atlantic Richfield Co. for financial support of this research.

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(16) Reaction to the hydride, rather than merely a reversion back to the TiO_2 starting material, was concluded based on the lack of similarities between spectrum C and E, as well as the presence of rhodium indicated in the hydride complex Auger spectrum.

(17) Control experiments involving hydrocarbon adsorption and thermal decomposition[14] of the supported diiallylrhodium species indicate that neither Rh particles nor hydrocarbon fragments are responsible for the features observed in Figure 1.

Triply Convergent Synthesis of (−)-Prostaglandin E_2[†]

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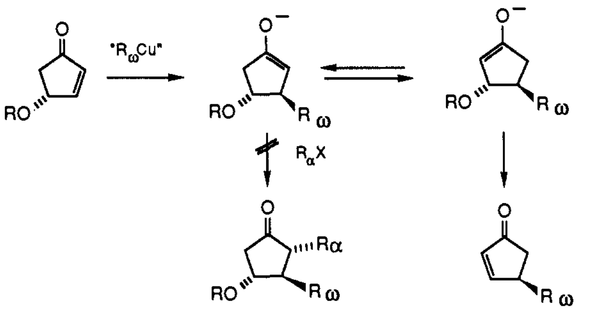
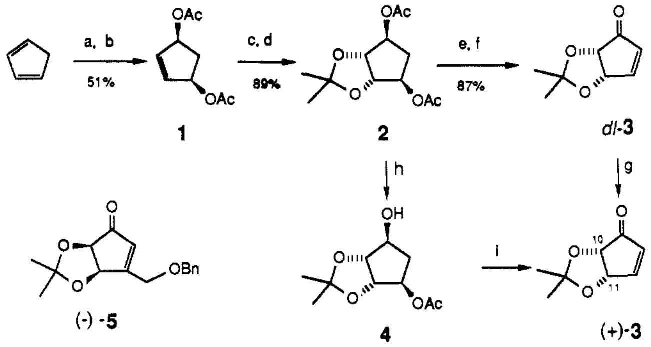
In prostaglandin syntheses, the three-component coupling approach, with its high convergence and potential for flexibility, has attracted considerable attention in recent years.[1] This approach involves the conjugate addition of the ω side chain to a protected 4-hydroxy-2-cyclopentenone, followed by trapping of the enolate with an alkyl halide containing the complete α side chain. A number of groups have reported indirect variations of this approach,[2] but in all the pioneering work the direct alkylation with an alkyl halide has failed,[3] due to enolate equilibration and elimination of the protected 4-hydroxy group (Scheme I). During the course of the work herein described, one solution to this equilibrium/elimination problem appeared; Noyori and coworkers[4a] found that the initially formed enolate (Scheme I) could be trapped at low temperatures as the *O*-(triphenylstannyl) derivative[4b,c] which, in turn, could be directly alkylated with excess $R_\alpha I$.

Scheme I



Scheme II[a]



[a] (a) O_2, *hν*, rose bengal, thiourea, MeOH;[6] (b) A_2O, pyridine, catalytic DMAP, CH_2Cl_2; (c) 1 mol % OsO_4, Me_3NO, THF, acetone; (d) acetone, catalytic TsOH; (e) KOH, MeOH; (f) dicyclohexylcarbodiimide, Me_2SO, pyridine, trifluoroacetic acid, benzene; (g) (+)-*N*,*S*-dimethyl-*S*-phenylsulfoximine resolution;[7] (h) electric eel acetylcholinesterase, H_2O, 25 °C; (i) CrO_3, H_2SO_4, acetone.

It appeared to us that enone **3** would be an ideal substrate for this three-component coupling process. We postulated that the presence of the α-oxygen functionality constrained in the five-membered ring would supress enolate equilibration (by a combination of charge repulsion and angle strain—double bond exo to 5-membered ring in unfavored enolate) and alkylation would occur regiospecifically to afford the trans vicinally dialkylated product. Reductive removal of the α-oxygen group would yield the PGE structural system.

Enone **3**[5] (mp 37.5–38.5 °C, lit.[5a] 36–38 °C) was synthesized in six steps in 40% overall yield from cyclopentadiene as shown in Scheme II. Optical resolution of **3** was achieved with (+)-*N*,*S*-dimethyl-*S*-phenylsulfoximine[7] to afford (+)-**3**, $[\alpha]^{25}_D$ +71.8° (*c* 0.91, $CHCl_3$), and (−)-**3**, $[\alpha]^{25}_D$ −70.8° (*c* 0.92, $CHCl_3$). On the basis of a comparative ORD study with (−)-**5** (+ Cotton effect) obtained from (−)-ribose,[8] (+)-**3** (− Cotton effect) was assigned the 10*S*,11*S* (PG numbering) absolute stereochemistry as shown in Scheme II. On the basis of earlier studies on enzymatic differentiation[9a] of the acetates of *meso*-**1**, we examined a number of esterase-catalyzed hydrolyses of *meso*-**2**. Success was variable until our attention was drawn to electric eel acetylcholinesterase by a recent report[9b] on the asymmetric hydrolysis of **1**. Treatment of **2** in aqueous suspension with electric eel acetylcholinesterase

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[†] Dedicated to Prof. Nelson J. Leonard on the occasion of his seventieth birthday.

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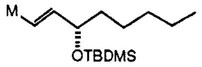
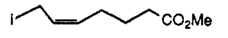
(ca. 1 mg of enzyme[9c]/g of **2**) provided monoacetate **4** (80%) which was oxidized with Jones reagent to enone (+)-**3** (95%, optical purity 98%).

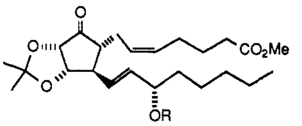
The optically active ω side chain vinylstannane **6a** was prepared from the alkyne[10a] by the light-initiated addition of tributyltin hydride[10b] and was transmetalated with *n*-BuLi in THF at −78 °C to afford **3b**.[10c] A phosphine-stabilized organocopper reagent[11] was prepared from **6b**, copper(I) iodide/tributylphosphine complex (1.0 equiv), and tributylphosphine (1.0 equiv) in THF at −78 °C. Addition of this copper reagent (1.1 equiv) to (+)-**1** at −78 °C, followed by direct alkylation of the resulting enolate with iodide **7**[12] (1.5 equiv) in the presence of HMPA (2.0 equiv) at −30 °C for 3 h, resulted in a 53% yield of the trans vicinally disubstituted product **8a**.[13,14] Desilylation with aqueous HF and pyridine in acetonitrile yielded **8b** in 89% yield.[15a] Reduction with Al(Hg) in aqueous THF furnished (−)-PGE$_2$ methyl ester (**9a**), $[\alpha]^{25}_{D}$ −78.8° (*c* 1.25, MeOH) [lit.[2c] $[\alpha]^{25}_{D}$ −71.7° (*c*, 1.04, MeOH)], in 98% yield;[15b] no diastereomers of **9a** could be detected by high-field ^{1}H or ^{13}C NMR of the product. Ester **9a** has previously been converted to (−)-PGE$_2$ (**9b**) by enzymatic ester hydrolysis.[16] The 5,6-didehydro analogue **9c** was also synthesized in racemic form in a similar manner in 51% overall yield from **3**.



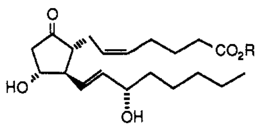
6a M = Bu$_3$Sn
b M = Li



7



8a R=TBDMS
b R=H



9a R = Me
b R = H
c 5,6-didehydro (C≡C)

We anticipate that the optically pure synthon **3** and the concepts herein demonstrated involving the use of the acetonide grouping to mask an aldol will be applicable to the synthesis of a number of biologically interesting substrates. We are continuing to explore these matters.[17,18]

Acknowledgment. The developmental work on the enone was supported by a grant from the National Science Foundation and was based on studies by Dr. Kevin Kunnen whose contributions we gratefully acknowledge. The application of the chemistry to the synthesis of prostanoids was supported by a grant from the National Institutes of Health.

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(10) (a) 3(*S*)-[(*tert*-Butyldimethylsilyl)oxy]-1-octyne ($[\alpha]^{25}_{D}$ −47° (Et$_2$O)) was kindly provided by Dr. P. W. Collins, G. D. Searle and Co. (b) Collins, P. W.; Jung, C. W.; Gasiecki, A.; Pappo, R. *Tetrahedron Lett.* **1978**, 3187. (c) Stannane **6a** was obtained as an 85:15 mixture of *trans*- and *cis*-vinylstannanes. Only *trans*-**6a** was transmetalated to an appreciable extent under the reaction conditions (see ref 10b).

(11) Suzuki, M.; Suzuki, T.; Kawagishi, T.; Morita, Y.; Noyori, R. *Isr. J. Chem.* **1984**, *24*, 118.

(12) Prepared by the method of: Corey, E. J.; Sachdev, H. S. *J. Am. Chem. Soc.* **1973**, *95*, 8483.

(13) The trans alkylation product was obtained in 46% yield along with 10% of the cis product, which was recycled to the desired **8a** by stirring with catalytic NaOAc in MeOH to provide **8a** in 53% overall yield. About 30% of product from addition of the lower side chain only was recovered from the reaction mixture; this material could be recycled to **8a** by treatment with LDA and **7**.

(14) All products were purified by "flash chromatography" on silica gel and gave satisfactory IR, ^{1}H NMR, ^{13}C NMR, exact mass, and/or elemental analysis.

(15) (a) Yield based on recovered starting material; isolated yield: 78%. (b) Yield based on recovered starting material; isolated yield: 89%.

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(18) The chemistry herein described is the subject of a patent application by Wayne State University.

Simplest Chloronium Radical. A Neutralization–Reionization Mass Spectrometry Study

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The hydrogen + chlorine chain reaction has been an exemplar in the development of the kinetics of elementary gas-phase reactions.[1] The barrier heights of the chain propagating step Cl$^\bullet$ + H$_2$ and of the symmetric atom-exchange H′$^\bullet$ + H″Cl → H′Cl + H″$^\bullet$ have been the subject of numerous recent experimental and theoretical investigations.[1c-e] An important intermediate in these reactions is the prototype chloronium radical, H$_2$Cl$^\bullet$, for which semiempirical calculations[1b] indicate that Cl–H–H structures are dynamically more stable than H–Cl–H structures. Here we report the preparation of stable ($\sim 10^{-6}$ s) H$_2$Cl$^\bullet$ by neutralization[2-5] of fast gaseous H$_2$Cl$^+$ ions, with the surprising apparent lifetimes HDCl ≫ H$_2$Cl > D$_2$Cl. In contrast, Porter has found[2] that the analogous H$_4$N$^\bullet$, H$_3$O$^\bullet$, and H$_2$F$^\bullet$ survive for $\sim 10^{-6}$ s only if they are perdeuterated.

To produce the neutralization–reionization (NR) mass spectra[2-5] (Figure 1),[6] 10-keV mass-selected H$_2{}^{37}$Cl$^+$ ions[7] are neutralized by Hg vapor (30% transmittance),[4b] residual ions are deflected electrostatically, and the resulting beam of fast neutrals is ionized by collision with He (90% or 30% transmittance).[4c] The presence of *m/z* 39 (40,41) proves that a substantial portion of the H$_2$Cl (HDCl, D$_2$Cl) neutrals formed upon Hg neutralization has survived undissociated, a lifetime >0.8 μs under our experimental conditions.[3c] Interaction times are $\sim 10^{-15}$ s, precluding bimolecular reactions.[2-5] Unexpectedly,[2] the reionization abundances show [HDCl$^+$] ≫ [H$_2$Cl$^+$] > [D$_2$Cl$^+$] (Figure 1, parts A, E, I). Further, these abundances decrease with increasing ion source pressure (Figure 1, parts A, E, I vs. parts C, G, K, respectively). The average bond lengths in H$_2$Cl$^+$ should be substantially less than those in H$_2$Cl$^\bullet$, causing an unfavorable Franck–Condon factor for the vertical transition H$_2$Cl$^+$ → H$_2$Cl$^\bullet$.[3d] Collisional cooling of the H$_2$Cl$^+$ ions (which should be formed with ~ 12 kcal mol^{-1} excess energy)[7,8] should thus decrease the proportion of ions which produce H$_2$Cl$^\bullet$ below the dissociation threshold. As a possible explanation of the isotope effects, the Franck–Condon overlap in neutralization could be decreased with deuterium, but this should be much less than the order of magnitude decrease caused by collisional cooling. Similarly, although deuterium substitution should stabilize the resulting chloronium

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(6) Full experimental details are published.[3,4]

(7) H$_2$Cl$^+$ is produced in a chemical ionization ion source from HCl$^{\bullet+}$ + HCl → H$_2$Cl$^+$ + Cl$^\bullet$, and D$_2$Cl$^+$ and DHCl$^+$ from DCl and DCl + HCl.

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