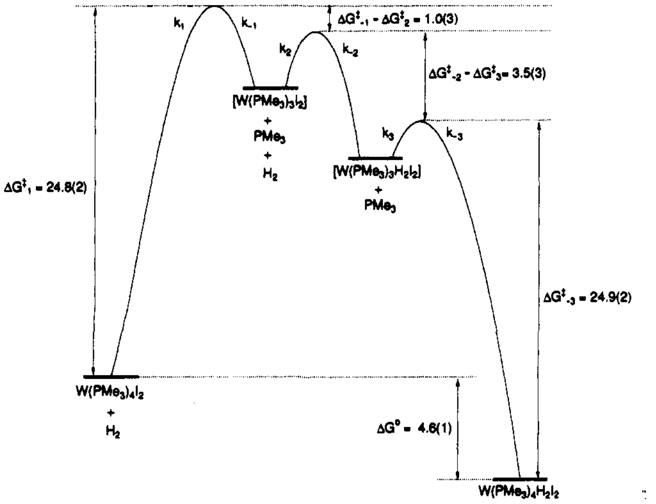

Figure 1. Energy surface for oxidative addition of H_2 to $W(PMe_3)_4I_2$ at 60 °C. Standard states of the components are 1 M, and energy values are in kilocalories/mole.

temperature dependence of K_D reveals that the origin of the inverse equilibrium deuterium isotope effect is enthalpic in nature [$\Delta H^{\circ}_{D} = -21.6$ (7) kcal mol^{-1}, compared to $\Delta H^{\circ}_{H} = -19.7$ (6) kcal mol^{-1}], since the W–D bond is substantially stronger than the W–H bond [D(W–D) = 63.8 (7) kcal mol^{-1} versus D(W–H) = 62.0 (6) kcal mol^{-1}].[11] Indeed, the small entropic difference [$\Delta S^{\circ}_{D} = -51$ (3) eu versus $\Delta S^{\circ}_{H} = -45$ (2) eu] actually attempts to counter the inverse nature of the equilibrium deuterium isotope effect.[13]

It is important to emphasize that an inverse equilibrium deuterium isotope effect for oxidative addition would *not* be predicted by consideration of the zero point energy differences associated with the observed W–H and W–D stretching frequencies alone.[14] Therefore, the inclusion of *bending* modes associated with the dihydride moiety is proposed to be responsible for an additional lowering of zero point energy for $W(PMe_3)_4D_2I_2$ with respect to $W(PMe_3)_4H_2I_2$.[15]

The mechanism of the oxidative addition/reductive elimination transformation has been investigated by kinetic studies. Interestingly, $W(PMe_3)_4H_2I_2$ is *not* obtained by the *direct* oxidative addition of H_2 to six-coordinate *trans*-$W(PMe_3)_4I_2$. Specifically, the oxidative addition is strongly inhibited by addition of PMe_3, so that a mechanism involving PMe_3 dissociation and a five-coordinate $[W(PMe_3)_3I_2]$ intermediate is implied. Oxidative addition of H_2 to $[W(PMe_3)_3I_2]$, followed by coordination of PMe_3, gives $W(PMe_3)_4H_2I_2$, as summarized in Scheme I. A similar scheme has previously been proposed by Halpern for hydrogenation of $Rh(PPh_3)_3Cl$.[16] As indicated by microscopic reversibility, the reductive elimination of H_2 from $W(PMe_3)_4H_2I_2$ must also proceed via initial PMe_3 dissociation. Accordingly, the reductive elimination of H_2 from $W(PMe_3)_4H_2I_2$ is also inhibited by addition of PMe_3. A detailed study of the kinetics of the oxidative addition and reductive elimination transformations has allowed the free-energy surface illustrated in Figure 1 to be established.[17] The primary kinetic deuterium isotope effect for oxidative addition of H_2 is $k_{2(H)}/k_{2(D)} = 1.2$ (2)],[18] whereas that for reductive elimination of H_2 is estimated to be $k_{-2(H)}/k_{-2(D)} \approx 2$.[19] Hence, since the kinetic deuterium isotope effect for reductive elimination is substantially larger than that for oxidative addition, an inverse equilibrium deuterium isotope effect is obtained.[20,21]

Acknowledgment. We are very grateful to Professor R. G. Bergman and Dr. M. Bullock for helpful discussions. We thank the donors of the Petroleum Research Fund, administered by the ACS, for support of this research. G.P. is the recipient of an A. P. Sloan Research Fellowship (1991–1993), a Camille and Henry Dreyfus Teacher-Scholar Award (1991–1996), and a Presidential Faculty Fellowship Award (1992–1997).

Supplementary Material Available: Kinetic and thermodynamic data for the $W(PMe_3)_4I_2/H_2(D_2)$ systems and crystal structure data for $W(PMe_3)_4I_2$ and $W(PMe_3)_4H_2I_2$ (17 pages); listing of observed and calculated structure factors for $W(PMe_3)_4I_2$ and $W(PMe_3)_4H_2I_2$ (20 pages). Ordering information is given on any current masthead page.

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(13) The origin of the difference in ΔS° for the oxidative addition of H_2 and D_2 is presumably the greater entropy of D_2 compared with that of H_2 (39.0 and 34.0 eu, respectively, at 300 K). See: Woolley, H. W.; Scott, R. B.; Brickwedde, F. G. *J. Res. Natl. Bur. Stand.* (*U.S.*) **1948**, *41*, 379–475.

(14) The observed ν_{W-H} and ν_{W-D} stretching frequencies of 1961 and 1416 cm^{-1}, respectively, result in a zero point energy difference of 273 cm^{-1} for this vibrational mode. If the symmetric and asymmetric stretches have similar frequencies, the combined zero point energy lowering would be less than the difference between D_2 and H_2 zero point energies (630 cm^{-1}), so that consideration of additional vibrational modes is required to produce the inverse equilibrium deuterium isotope effect.

(15) Relatively little information is available concerning the bending modes associated with transition metal hydride complexes. For a recent study on $[(\eta^5\text{-}C_5H_5)_2MH_n]^{x+}$ complexes, see: Girling, R. B.; Grebenik, P.; Perutz, R. N. *Inorg. Chem.* **1986**, *25*, 31–36.

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(17) It is likely that a dihydrogen species, for example, $[W(PMe_3)_3(\eta^2\text{-}H_2)I_2]$, may also be an intermediate on the energy surface. However, since our data is not capable of providing support either for or against such intermediates, we have excluded them from our treatment.

(18) The kinetic deuterium isotope effect for addition of H_2 to *trans*-$Ir(PPh_3)_2(CO)Cl$ is of a similar magnitude ($k_H/k_D = 1.06$ at 30 °C). Zhou, P.; Vitale, A. A.; San Filippo, J., Jr.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1985**, *107*, 8049–8054.

(19) The estimate $k_{-2(H)}/k_{-2(D)} \approx 2$ is based on the assumption that the secondary isotope effect for addition of PMe_3 to $[W(PMe_3)_3H_2I_2]$ is negligible (i.e., $k_{3(H)}/k_{3(D)} \approx 1$).

(20) An inverse equilibrium deuterium isotope effect has also been observed for the oxidative addition of dihydrogen to *trans*-$Ir(PPh_3)_2(CO)Cl$.[20a–c] A composite primary and secondary inverse equilibrium deuterium isotope effect has also been observed for the oxidative addition of dihydrogen to $Cp_2Ta(\mu\text{-}CX_2)_2Ir(CO)(PPh_3)$ (X = H, D).[20d] (a) Vaska, L.; Werneke, M. F. Manuscript in preparation. (b) Werneke, M. F. Ph.D. Thesis, Clarkson College of Technology, Potsdam, NY, 1971. (c) Goldman, A. Personal communication. (d) Hostetler, M. J.; Bergman, R. G. *J. Am. Chem. Soc.* **1992**, *114*, 7629–7636.

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Generation of Enantiopure *trans*-$\Delta^{9,10}$-Tricyclo[9.3.1.0^{3,8}]pentadecene Diastereomers from a Single Precursor. Control of Stereochemistry by Means of Rotationally Restrictive Nonbonded Interactions

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The resolvability and optical stability of medium-sized *trans*-cycloalkenes has been of interest for 30 years.[1-3] Molecular asymmetry of this type can be established because of steric inhibition to internal rotation relative to the remainder of the ring of the σ-bonds flanking the (E)-alkene subunit. Although the structural implications of these factors are well understood, they have to our knowledge never been applied in a synthetic context. Our interest in the de novo acquisition of taxanes[4] has led us to

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(1) (a) Cope, A. C.; Ganellin, C. R.; Johnson, H. W., Jr.; Van Auken, T. V.; Winkler, H. J. S. *J. Am. Chem. Soc.* **1963**, *85*, 3276. (b) Cope, A. C.; Mehta, A. S. *J. Am. Chem. Soc.* **1964**, *86*, 1268. (c) Cope, A. C.; Pawson, B. A. *J. Am. Chem. Soc.* **1965**, *87*, 3649.

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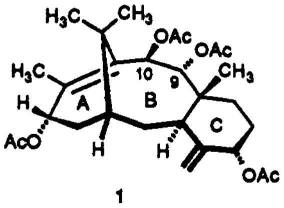
prepare a pair of diastereomerically related, optically pure, tricyclic *trans*-cyclooctenes from a common precursor and to take advantage of the barrier to their thermal interconversion for controlling the relative (and absolute) stereochemical course of subsequent functionalization reactions. Specifically demonstrated is a notably direct means for setting the 9,10-diacetoxy substitution plan characteristic of taxusin (1).[5]



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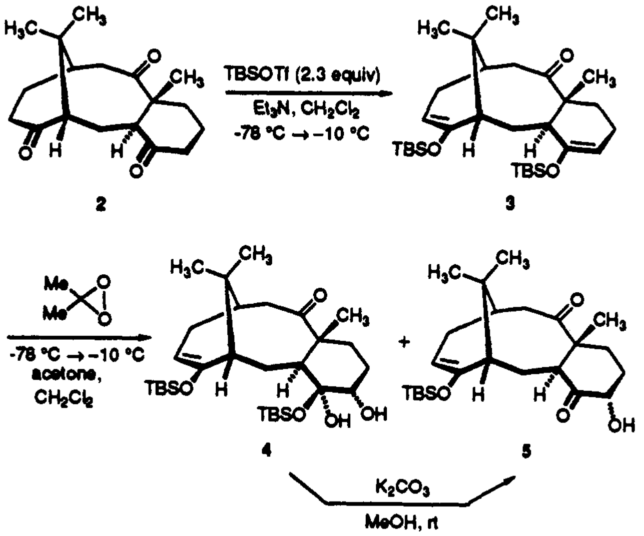
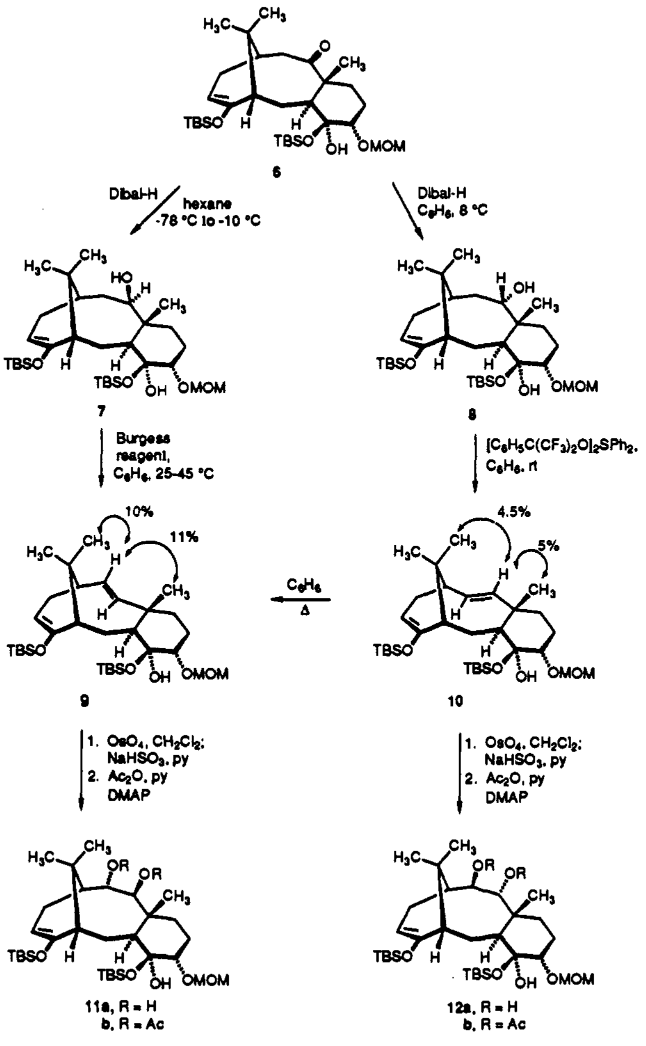
The triad of carbonyl groups present in the readily available triketone 2 (>97% ee)[6] is distinguished by its diverse reactivity. An expedient means for differentiating them efficiently consists of conversion to 3 (90%) with 2 equiv of TBSOTf and Et_3N, followed by exposure of this bis(silyl enol ether) to dimethyldioxirane[7] in the cold (Scheme I). Steric factors resident in 3 permit oxidation to occur at ring C without interference from the functionality in ring A. The major product of this oxidation is the unusual compound 4 (75%), whose structural assignment has been corroborated by X-ray crystallography.[8] The minor product 5 (17%), believed to be an artifact of the workup, can be generated quantitatively by exposure of 4 to K_2CO_3 in methanol at room temperature.[9]

The hemiketal unit in 4 is sufficiently stable to function directly as a blocking group. Conventional condensation with MOMCl has provided 6 in 95% yield (Scheme II). Its treatment with Dibal-H *in hexane at -78 to -10 °C* results in reduction of the preferred "carbonyl-up" conformer[4] to deliver β-alcohol 7 in 97% yield. This diastereoselectivity can be completely reversed by performing the reduction *in benzene solution at 8 °C*, these conditions leading quantitatively to α-alcohol 8. Presumably, the more elevated reaction temperature is adequate to allow the ketone–Dibal-H complex to adopt the sterically less congested "carbonyl-down" geometry prior to hydride delivery from the exo direction. The configurations of 7 and 8 were assigned on the basis of the stereospecificity of their respective dehydrations.

Scheme I



Scheme II



As a consequence of the preceding discovery, advantage could be taken of the latent potential of these alcohols for conversion to the *trans*-cycloalkenes 9 and 10. The rather inflexible nature of 7 serves to project the C-9 hydroxyl into a relationship essentially coplanar with H-10α and orthogonal to H-10β. For this reason, stirring 7 with the Burgess reagent[10] in warm benzene (25 → 45 °C) results in smooth conversion to 9 (70%), $[\alpha]^{20}_D$ $-125.0°$ (*c* 1.03, hexanes). Because α-alcohol 8 is insufficiently reactive toward this inner salt below 45 °C, alternative recourse was made to Martin's sulfurane[11] (benzene, room temperature) for obtaining 10 (91%), $[\alpha]^{20}_D$ $+42.3°$ (*c* 1.96, hexanes). Both olefinic products exhibit the large vinyl/vinyl coupling constant characteristic of (*E*)-cyclooctenes (J = 17.4 Hz for 9; J = 18.7 Hz for 10).[12] The

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crux of the issue, the specific manner in which the trans double bonds are positioned within the taxane framework, was deduced through the combined adaptation of one-bond $^1H/^{13}C$ COSY correlation and NOE experiments.[13] Several of the more diagnostic measurements are given in the illustrations.

Molecular mechanics calculations (MODEL version KS 2.96)[14] provided indication that **9** might be as much as 3 kcal/mol more thermodynamically stable than **10**. Indeed, heating **10** in C_6D_6 at 67 °C resulted in its *unidirectional* conversion to **9**, $k_1 = 2.58 \times 10^{-4}\ s^{-1}$, $t_{1/2} = 45$ min. The relative ease of this diastereomeric interconversion places **10** closer to *trans*-cyclononene ($t_{1/2} \approx 4$ min at 0 °C)[3] than to *trans*-cyclooctene ($t_{1/2} = 122$ h at 132.7 °C)[1c] in the intrinsic ability of these molecules to overcome their internal rotational barriers. The thermal stability of **10** is, however, more than adequate to allow for its individual utilization in synthesis, thus providing a new dimension to this area of chemistry.

Both **9** and **10** undergo osmylation to give diols **11a** (60%) and **12a** (84%), respectively, by electrophilic attack from the only available direction external to the ring. Subsequent acetylation provided **11b** and **12b** efficiently.

In summary, this study has established the feasibility of controlling stereochemistry by means of rotationally restrictive nonbonded interactions and laid the groundwork for possible entry to various taxanes including **1** by this useful tactic. Our current efforts are focused on these applications.

Acknowledgment. We are grateful to the Bristol-Myers Squibb Company for their financial support, to Dr. Dirk Friedrich for his assistance with the NMR experiments, and to Eugene Hickey for the molecular modeling studies.

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Dendritic Analogues of Engineering Plastics: A General One-Step Synthesis of Dendritic Polyaryl Ethers

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Dendritic or cascade polymers in which the ratio of branch sites to repeat units approaches unity have emerged recently as an important new concept in macromolecular design. We report here the first general single-step route to dendritic polyaryl ethers which are hyperbranched analogues of linear polyaryl ethers, a common class of engineering plastics. Specifically, we have prepared a family of four polymers based on aryl ethers by polymerization of AB_2 monomers, each of which contains a single phenolic hydroxyl group and two aryl fluorides which are activated toward nucleophilic displacement by carbonyl, sulfone, or tetrafluorophenyl moieties.[1,2] High molecular weights can be achieved with low polydispersities; molecular weights can be controlled by reaction conditions, and some properties of the polymers have been examined.

Although Flory proposed that polymerization of AB_x ($x \geq 2$) monomers should yield highly branched but soluble polymers,[3] most dendritic macromolecules have been prepared by stepwise processes which yield highly monodisperse, structurally precise materials in small quantities.[4] The time and labor involved in stepwise processes make the resulting materials too expensive for virtually any commodity application. Several groups have carried out one-step syntheses of dendritic macromolecules based upon AB_x monomers.[5-10] The first example by Webster and Kim yielded low molecular weight brominated polyphenylenes with a DP (degree of polymerization) of ca. 25 by polymerization of (3,5-dibromophenyl)boronic acid.[5] Later, Kim demonstrated the polymerization of the dihydrochloride salt of diaminobenzoyl chloride, yielding polyamides,[7] and Fréchet demonstrated the polymerization of bis(trimethylsiloxy)benzoyl chloride, yielding polyesters.[8] None of the existing one-step polymerizations of AB_x monomers permits control over the molecular weights of the final polymers.

Treatment of monomers **1a–d** in THF with an excess of NaH yielded solutions of their sodium salts (Scheme I). The solutions were filtered to remove excess NaH; the THF was removed in vacuo, and dimethylacetamide (DMA) or dimethyl sulfoxide (DMSO) was added. Heating the resulting solutions for 0.5–2 h at 100–180 °C effected polymerization. The resulting reaction mixtures were cooled and filtered to remove NaF, precipitated into 1 N HCl or 10% 1 N HCl in methanol, filtered, and dried. Polymerizations of **1a** and **1b** were insensitive to temperature, but polymerizations of **1c** and **1d** at 140 °C yielded insoluble gels, presumably caused by cross-linking due to reaction of the acetylene moieties. Polymerization at 100 °C yielded completely soluble polymers.

The molecular weights of polymers **2a** and **2b** were significantly affected by monomer concentration in the polymerization reaction. Higher concentrations yielded higher average molecular weights and broader molecular weight distributions (Table I). Adventitious H_2O in the DMA may be responsible. Alternatively, at lower concentrations, unimolecular termination reactions such as cyclization of a phenolate with one of the many activated aryl fluorides surrounding it in the same molecule are favored. At higher concentrations bimolecular reactions are favored, yielding higher molecular weight materials before termination. Two lines of evidence argue for the latter explanation. The molecular weights appear to be independent of the solvent, and we have been unable to find any sign of unreacted terminal hydroxyl groups in the products by ^1H NMR spectroscopy, particularly in the low mo-

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(1) The nucleophilic aromatic substitution reaction employed as our polymerization reaction is widely used in the preparation of linear polyaryl ethers. See: Johnson, R. N.; Farnham, A. G.; Clendinning, R. A.; Hale, W. F.; Merriam, C. N. *J. Polym. Sci., Polym. Chem. Ed.* **1967**, *5*, 2375. Hergenrother, P. M.; Jensen, B. J.; Havens, S. J. *Polymer* **1988**, *29*, 358. Singh, R.; Hay, A. S. *Macromolecules* **1992**, *25*, 1017.

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