electrophiles, and it was converted (CF_3SO_3Me in CH_2Cl_2, 20 °C; 88% yield) into the η-1-methylpyrrole dihydrido cation **3**, in the hope that the positive charge would promote nucleophilic attack, as occurs with cationic arene complexes.[3]

This first approach to the nucleophilic alkylation of pyrrole proved disappointing. Although the dihydrido cation **3** reacted smoothly (THF, 0 °C) with $LiAlH_4$ and $LiAlD_4$ to give (93% yield) the neutral dihydrido complexes **6**-H and **6**-D[8] [which were converted into 1-methylpyrrole (**9**-H) and 1-methyl-[2-^{2}H]pyrrole (**9**-D)[9] by heating in C_5D_5N (90 °C, 10 min)], only intractable mixtures were obtained with lithium alkyls or dimethyl sodiomalonate.

We have discovered, however, that lithium alkyls readily alkylate the neutral η-pyrrolyl iodo hydrido complex **4**, obtained in 80% yield by treatment of **2** with I_2 (1 equiv) and K_2CO_3 (excess) (CH_2Cl_2, 20 °C). Thus, **5a** was formed immediately and essentially quantitatively (92% isolated yield) when a solution of MeLi (1.2 equiv) was added to **4** (in THF, 0 °C); similarly, *n*-BuLi gave **5b** (90%), and *t*-BuLi (at −80 °C) gave **5c** (97%). The η-2-alkylpyrrolyl complexes **5a–c** could be converted into the free 2-alkylpyrroles **7a–c**[10] (**5a** and **5b** by heating at 90 °C in Me_2SO-d_6 containing HBF_4, and **5c** by vacuum pyrolysis at 150–180 °C).

The procedure could be repeated; the η-2-methylpyrrolyl complex **5a**, when treated successively with I_2–K_2CO_3 and MeLi, without isolating the intermediate iodo hydrido complex, gave the η-2,5-dimethylpyrrolyl complex **8a** (94% isolated yield). A special effort was made in this case to determine the regioselectivity of the reaction; no trace of the 2,3- or 2,4-dimethylpyrrolyl isomers could be detected in the crude, unrecrystallized η-2,5-dimethylpyrrolyl complex **8a** by 200-MHz ^{1}H NMR, indicating that the reaction is >98% regioselective.

$LiAlH_4$ and $LiAlD_4$ also reacted with the iodo hydrido complex **4**, but much more slowly (THF, 20 °C, 2 h), to give **5** (R = H) (≡**2**) and its 2-deuterio analogue **5** (R = D) (79% yield).[11]

This remarkably facile alkylation (**4** → **5**), in which nucleophilic attack on a coordinated aromatic moiety is accompanied by migration of hydrogen from carbon to metal and elimination of a good leaving group (halide) from the metal, appears to have some precedent in cyclopentadienyl transition-metal systems.[12] The presence of a leaving group is essential; the dihydrido complex **2** is not alkylated by lithium alkyls under the same conditions. We imagine that the reaction is either an entirely concerted nucleophilic process or, more probably, that it is initiated by a single electron transfer, followed by loss of iodide from the 19e radical anion of **4**.

Note Added in Proof. Since this communication was submitted, we have found that *aromatic* lithium reagents also react with the iodo hydrido complexes under the same conditions (0 °C), and with the same high regioselectivity and yield, as the aliphatic lithium reagents described above. Thus, **5** (R = Ph) and **5** (R = 5-methyl-2-furyl) were obtained from **4** in >85% yield. **8** (R = Ph) was obtained from **5** (R = Ph) in 87% yield without isolating the iodo hydrido intermediate and afforded pure 2,5-diphenylpyrrole (92%, no isomers detectable by NMR) upon treatment with Me_2SO–HBF_4.

(8) (a) The ^{1}H NMR and IR spectra of **6**-H and **6**-D indicate that hydride attacks the 1-methylpyrrole ring in **3** from the uncomplexed, exo side. The splitting pattern of the NMR signal of the introduced hydrogen (δ 5.22, absent in the spectrum of **6**-D) can be explained by long-range coupling with the two ^{31}P nuclei, characteristic for H-exo.[8b] Furthermore the medium-intensity band at 2820 cm^{-1} (ν(C–H) exo) in the IR spectrum of **6**-H is absent in the spectrum of **6**-D, in which ν(C–D) exo is observed at 2030 cm^{-1}. (b) Davies, S. G.; Moon, S. D.; Simpson, S. J.; Thomas, S. E. *J. Chem. Soc., Dalton Trans.* **1983**, 1805–1806.

(9) **9**-H was identified, without isolation, by comparison of its ^{1}H NMR spectrum with that of a commercial sample; integration of its ^{1}H NMR signals showed that **9**-D was deuteriated exclusively on C-2.

(10) **7a** and **7b** were identified, without isolation, by their ^{1}H NMR spectra.[2a] **7c** was isolated in 84% yield: ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.04 (br, NH) 6.69 (m, H5), 6.12 (m) and 5.94 (m) (H3, H4), 1.25 (s, *t*-Bu).

(11) Integration of its ^{1}H NMR signals showed that **5** (R = D) was deuteriated exclusively on C-2.

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Design of Stereoselective Etchants for Organic Crystals. Application for the Sorting of Enantiomorphs and Direct Assignment of Absolute Configuration of Chiral Molecules

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Despite the widespread use of etching in the material sciences,[1-3] the selection of appropriate etchants is generally done with a combination of "inspiration and intuition".[1]

Recently we reported changes in crystal habit induced during crystallization by the presence of minute amounts of additives with structures similar to that of the substrate.[4] A correlation was established between the molecular structure of the additive, the crystal structure of the substrate, and the affected growth directions. We found that the additive may bind stereoselectively to the affected crystal face, as if it were a substrate molecule, on the condition that its modified moiety emerges from the crystal surface. During the crystal's growth this adsorption hinders growth by disturbing deposition of oncoming layers on that face. During dissolution such additive molecules should adsorb in an analogous stereoselective manner only at those faces whose molecules are so oriented as to receive this additive. We report that a growth inhibitor of a particular face can act as an etchant of that same face during partial dissolution. The two examples covered here deal with etching by chiral additives of a mixture of enantiomorphous crystals of (*R*,*S*)-asparagine which, as a conglomerate, resolves spontaneously on crystallization and with the etching by chiral additives of the enantiotopic faces of the centrosymmetric crystal of glycine.

Growth experiments have shown that only *R* amino acid additives may bind to the surfaces of (*R*)-asparagine crystals, while the *S* additives may bind only to the (*S*)-asparagine crystals.[4a] The additive aspartic acid may bind only to those crystal faces of asparagine which allow its modified moiety, the hydroxyl oxygen, to emerge from the crystal surface, i.e., the {010} face (Figure 1a). A loss of energy due to replacement of the N—H···O- (carboxylate) hydrogen bond between asparagine molecules by an O···O repulsion between the hydroxyl oxygen of the β-carboxy group of aspartic acid and the carboxylate oxygen of asparagine inhibits the aspartic acid's adsorption when it approaches an {010} face in the reverse manner.[5] The conditions necessary for binding are met in two out of the four symmetry-related sites at the {010} faces of this orthorhombic $P2_12_12_1$ crystal.[6] When crystalline (*R*,*S*)-asparagine–H_2O is partially dissolved in a solution containing 20% (*R*)-aspartic acid, etch pits are formed only on the {010} faces[7] of the *R* crystals (Figure 1b); the *S* crystals remain

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(3) Johnston, W. G. *Prog. Ceram. Sci.* **1963**, *3*, 42.

(4) (a) Addadi, L.; Berkovitch-Yellin, Z.; Domb, N.; Gati, E.; Lahav, M.; Leiserowitz, L. *Nature (London)* **1982**, *296*, 21. (b) Berkovitch-Yellin, Z.; Addadi, L.; Idelson, M.; Leiserowitz, L.; Lahav, M. *Nature (London)* **1982**, *296*, 27.

(5) Verbist, J. J.; Lehman, M. S.; Koetzle, T. F.; Hamilton, W. C. *Acta Crystallogr., Sect. B* **1972**, *B28*, 3006.

(6) Berkovitch-Yellin, Z.; Addadi, L.; van Mil, J.; Lahav, M.; Leiserowitz, L., unpublished results.

(7) The crystals of asparagine were partially dissolved in a solution containing 50 mg of (*R*,*S*)-asparagine and 10 mg of (*R*)-aspartic acid per 1 mL of H_2O at 25 °C for 5 min. The etching was seen on the {010} faces under both optical and scanning electron microscopes.

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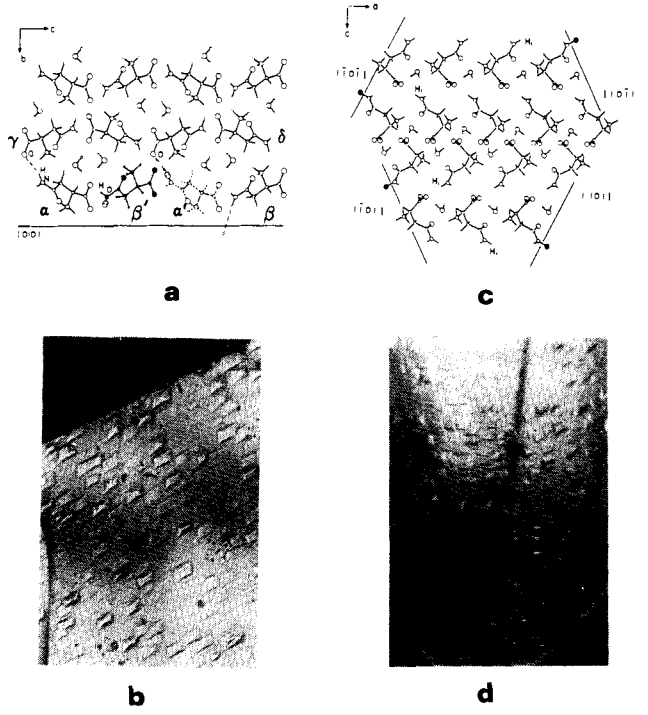

Figure 1. (a) (*S*)-Asparagine–H_2O: Packing arrangement showing the four symmetry related molecular sties α, β, γ, δ. The (010) faces shown contain the surface sites α and β (were this surface layer removed sites γ and δ would form the surface layer). The α and β sites are occupied by asparagine molecules related by a 2_1 axes along *c*. The corresponding α' and β' sites are drawn to be occupied by aspartic acid molecules. Aspartic acid may be adsorbed only at site β' or β but not at site α' or α (see text). (b) Crystals of (*R*)-asparagine–H_2O etched with (*R*)-aspartic acid. Etch pits are formed on the {010} faces. (c) (*S*)-Asparagine–H_2O: Packing arrangement showing the four {101} faces. The molecular sites on these faces at which (*S*)-*N*-methylasparagine may be adsorbed are indicated. (d) Two (101) and (10$\bar{1}$) surfaces of (*S*)-asparagine–H_2O etched with *N*-methylasparagine. The intersection of these two faces forms a dark edge which runs parallel to the *b* axis.

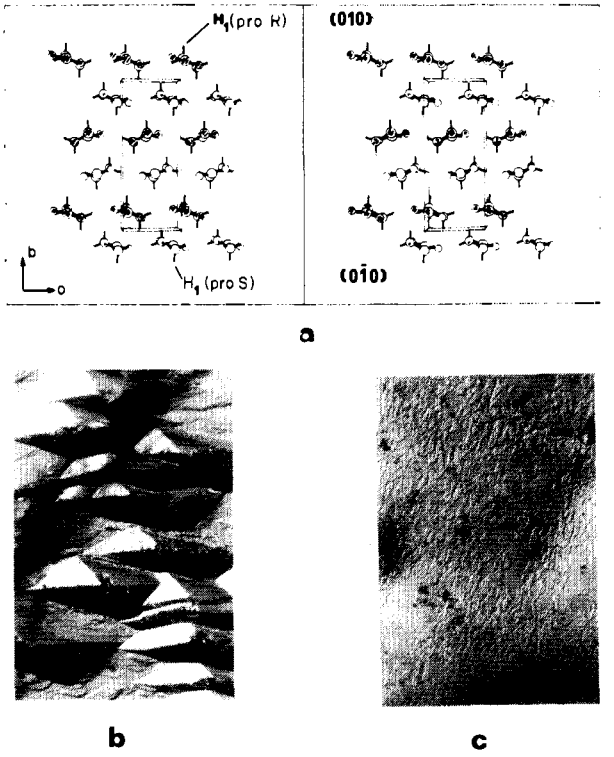

Figure 2. (a) Packing arrangement of α-glycine. (b) The (010) surface of a platelike crystal of α-glycine dissolved in the presence of (*R*)-alanine. The sides of the etch pits are aligned along the A and C axes. (c) Etch pits are not formed on the (0$\bar{1}$0) of the same glycine crystal when dissolved in the presence of (*R*)-alanine.

Scheme I

unetched. These differences in the surfaces of the two enantiomorphic crystals after dissolution enables one to sort the *R* and *S* crystals manually.[8a,b] By symmetry, the {010} faces of only the (*S*)-asparagine crystals are etched by (*S*)-aspartic acid. The pits of these *R* and *S* crystals have their external surface in the form of parallelograms, exhibiting distinctive handedness.

We predicted that *N*-methylasparagine could be used as an additive to induce etching on the {101} faces of asparagine because the *N*-Me group may replace the emerging N–H of asparagine at a {101} face[9] (Figure 1c). Indeed this additive causes etching on the {101} and {111} faces. The etch pits on the {101} faces are distinct asymmetric scalene triangles (Figure 1d).

Glycine crystallizes from water solution in the centrosymmetric $P2_1/n$ α-form.[10] Growth in the presence of racemic α-amino acids yields {010} plates because the *R* and *S* acids may be adsorbed only on the (010) and (0$\bar{1}$0) faces, respectively.[11] This enantioselective adsorption on the {010} surfaces arises from the fact that the hydrogen atom of C–H_1 which emerges from the (010) face is *pro-R*, replaceable by side chains of *R* α-amino acid additives, while, by inversion symmetry, the hydrogen of C–H_1 which emerges from the (0$\bar{1}$0) face is *pro-S*, replaceable by side chains of *S* α-amino acid additives (Figure 2a). When these plates are partially dissolved in the presence of (*R*)-alanine, well-formed, rhombic etch pits with sides parallel to the *a* and *c* axes develop on the (010) face[12] (Figure 2b). The (0$\bar{1}$0) face of that same crystal dissolves smoothly (Figure 2c). By symmetry, (*S*)-alanine induces etch pits only on the (0$\bar{1}$0) face. Racemic alanine additive causes etching of both (010) and (0$\bar{1}$0) faces. This etching has been observed with 19 different α-amino acids, the shape of the pits sometimes varying with the amino acid used.[13]

It is established that an etch pit will form at the site of an emergent dislocation. Moreover, it was suggested by Frank that the crystal surface must be poisoned by an impurity in order for that etching to be made apparent.[14] The same behavior is expected at such a site where the additive may adhere stereoselectively to, say, only horizontal surfaces hindering dissolution therefrom. Scheme I illustrates how additives (shown as black

(8) (a) More than 15 separations were performed, utilizing more than 100 crystals. Optical rotation of each etched sample in 5 N HCl was done at room temperature to confirm the handedness of the crystals. The average enantiomeric excess was 98.0 ± 1.7%. As the weight of the crystals used was above 5 mg in all cases, this deviation from absolute separation is most likely due to mechanical deposition of the *S* chiral additive on the (*R*)-asparagine crystals. (b) For a description of other methods for resolving enantiomorphic crystals, see: Lin, C. T.; Curtin, D. Y.; Paul, I. C. *J. Am. Chem. Soc.* **1974**, *96*, 6199.

(9) In secondary amides the C=O is always trans to the N—H bond. Leiserowitz, L.; Tuval, M. *Acta Crystallogr., Sect. B* **1978**, *B34*, 1230.

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(11) Weissbuch, I.; Addadi, L.; Berkovitch-Yellin, Z.; Gati, E.; Weinstein, S.; Lahav, M.; Leiserowitz, L. *J. Am. Chem. Soc.* **1983**, *105*, 6615.

(12) Glycine plates were grown by slow evaporation from solutions of 750 mg of glycine and 7.5 mg of (*R,S*)-alanine per 3 mL of H_2O. These plates were etched in solutions of 600 mg of glycine and 75 mg of (*R*)-alanine per 3 mL of H_2O at 27 °C for 3 min. Etching of the (010) face was seen under both the optical and scanning electron microscopes.

(13) Crystals were dissolved at 27 °C with 600 mg of glycine in 3 mL of H_2O and the amount of α-amino acid additive listed below in mg × 10: Arg 30, Asn 20, Asp 5, Cys 10, Gln 10, Glu 10, His 10, Lys 20 Met 5, Orn 10, Phe 5, Ser 20, Thr 25, Typ 10, Val 10, Leu 0.3, Ile 0.3, Tyr 0.6. Etching was not seen with proline as expected.

(14) Frank, F. C. "Growth and Perfection of Crystals"; Wiley: New York, 1957; pp 411–419. Work along these lines has been carried out extensively on the inorganic crystals of LiF dissolved in presence of FeF_3.[15,16]

(15) Gilman, J. J.; Johnston, W. G.; Sears, G. W. *J. Appl. Phys.* **1958**, *29*, 5.

(16) Ives, M. B.; Hirth, J. P. *J. Chem. Phys.* **1960**, *33*, 2.

dots) stereoselectively poison the exposed horizontal surfaces within a defect, leading to etch-pit formation. Other surfaces at this site will dissolve unperturbed. Such a process could enhance the depth of the etch pit.

We may conclude that stereoselective etching of a chiral crystal by an optically pure, tailor-made additive provides a means of manually sorting enantiomorphic crystals and of correlating the absolute configuration of the etchant and the etched (or unetched) crystals. Furthermore such etching allows one to directly assign the absolute configuration of chiral desolved additives (e.g., the α-amino acids) by their effect on centrosymmetric crystals (e.g., α-glycine). We have applied this stereoselective etching to other systems such as cinnamide, allopurinol, serine, and glutamic acid hydrochloride and for the assignment of the absolute direction of polar crystals whose constituent molecules are nonchiral, such as the γ-form of glycine, which will be discussed elsewhere.

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Registry No. (*R*)-Asparagine monohydrate, 5794-24-1; (*S*)-asparagine monohydrate, 5794-13-8; (*R*)-aspartic acid, 1783-96-6; *N*-methylasparagine, 7175-34-0; α-glycine, 56-40-6; (*R*)-alanine, 338-69-2.

Olefin Insertion in a Metal Alkyl in a Ziegler Polymerization System

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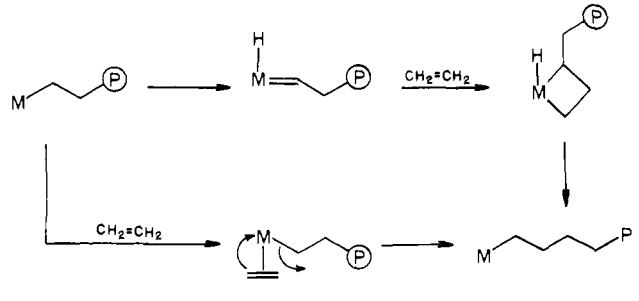
Ziegler–Natta polymerization is the backbone of the polyolefin business and remains as one of the key processes in organometallic chemistry. After more than 30 years of intensive study, many questions concerning the basic steps in this process remain unanswered. Basic to the understanding of this reaction is the mechanism of the insertion of an olefin into a metal–carbon bond. Of the variety of mechanisms that have been proposed, two distinct classes have emerged and have been modeled. Cossee proposed the direct insertion of the olefin into the growing polymer.[1] More recently, Green and Rooney proposed that the reaction proceeds through a metathesis-type mechanism.[2] The only difference between these two mechanisms is the interaction of a hydrogen on the α-carbon with the metal center in the latter. Before further progress can be made in the understanding of the basic mechanistic and stereochemical steps of this reaction, this division of mechanisms must be established. Excellent models exist for each of the proposed classes of mechanisms.[3,4]



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(2) Ivin, K. J.; Rooney, J. J.; Stewart, C. D.; Green, M. L. H.; Mahtab, J. R. *J. Chem. Soc., Chem. Commun.* **1978**, 604.

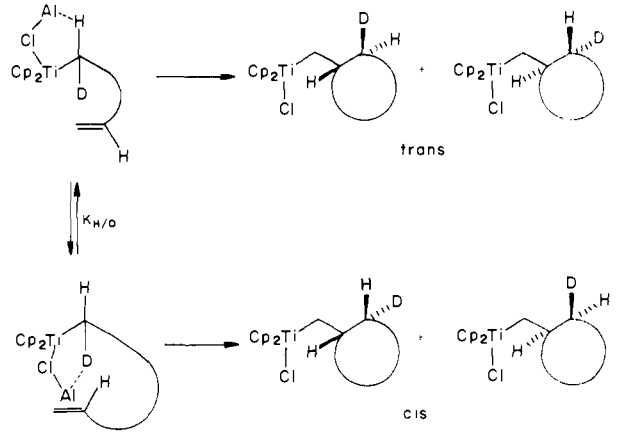
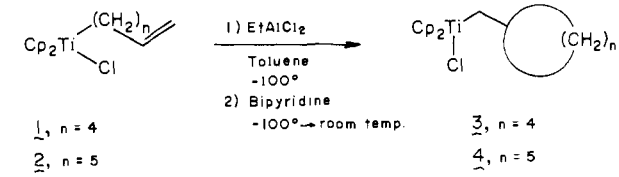


Figure 1.

The first of our approaches required the measurement of a precise kinetic isotope effect on the polymerization of ethylene.[5] Since no kinetic isotope was observed, the Cossee mechanism was favored since it does not involve α-H activation. However, due to the complexity of the catalytic system and the possibility of the masking of the key carbon–carbon bond-forming step, a more direct approach to the problem was sought. Since in the polymerization of an α-olefin the stereochemistry is set in the carbon–carbon bond-forming step, a system has been developed that will show an *isotope effect on the stereochemistry* of olefin insertion if the α-hydrogens are involved in this key reaction. This is the most direct and precise method to probe for such a C–H interaction.

The best studied of the original Ziegler-type systems is the titanocene ethyl chloride/ethylaluminum dichloride catalyst.[6] Thus, a series of titanocene alkenyl chlorides were prepared.[7] The



pendant olefin, appropriately situated for Lewis acid induced intramolecular insertion, provides a high local concentration while maintaining a 1:1 stoichiometry of olefin to metal center. These alkenyl chlorides are stable for long periods at room temperature but cyclize to the corresponding titanocene metallocycloalkanes on treatment with 1–10 equiv of ethylaluminum dichloride at −100

(3) Watson, P. L. *J. Am. Chem. Soc.* **1982**, *104*, 337.
(4) Turner, H. W.; Schrock, R. R. *J. Am. Chem. Soc.* **1983**, *105*, 4942.
(5) Soto, J.; Steigerwald, M.; Grubbs, R. H. *J. Am. Chem. Soc.* **1982**, *104*, 4479. Arguments in this paper suggest that isotope effects of >1.5 are expected.
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(7) (a) Compounds **1–4** were prepared by treating Cp_2TiCl_2 with the appropriate Grignard reagent at −30 °C in THF. After 10 min the solution is warmed to room temperature and stirred for 2 h. After concentrating the solution and adding hexane, the solution is filtered and cooled to −50 °C to give red needles in all cases. **1**: ^{1}H NMR (C_6D_6) δ 1.0–1.8 (m, 4 H), 1.5 (s, br, 2 H), 2.0 (q, 2 H), 4.97 (d, 1 H, J = 1 Hz), 5.12 (dd, 1 H, J = 6 Hz, 1 H), 5.85 (s, 10 H), 5.6–6.0 (unresolved dd under Cp peak, 1H); ^{13}C NMR (C_6D_6) δ 33.7, 34.5, 37.2, 72.1, 114.4, 115.6, 139.6. **2**: ^{1}H NMR (C_6D_6) δ 1.0–1.9 (m, 6 H), 1.57 (s, 2 H), 2.04 (q, 2 H), 4.97 (d, H, J = 1 Hz), 5.12 (dd, 1H, J = 6 Hz, 1 H), 5.7–6.0 (unresolved dd under Cp peak, 1 H), 5.78 (s, 10 H); ^{13}C NMR (C_6D_6) δ 28.9, 34.4, 34.9, 37.8, 72.6, 114.4, 115.6, 139.4. (b) **4**: ^{1}H NMR (C_6D_6) δ 1.3–1.7 (m, 9 H), 1.66 (d, J = 5.6 Hz, 2 H), 5.81 (s, 10 H); ^{13}C NMR (C_6D_6) gated decoupled δ 25.3 (t, $^1J_{CH}$ = 125.9 Hz, C(3) and C(4) of cyclopentyl), 37.2 [t, $^1J_{CH}$ = 131.8 Hz, C(2) and C(5) of cyclopentyl], 48.3 [d, $^1J_{CH}$ = 127 Hz, C(1) of cyclopentyl], 82.5 (t, $^1J_{CH}$ = 125 Hz, C(α)), 115.5 (d, ^1J = 174 Hz, Cp). **4**: ^{1}H NMR (C_6D_6) δ 0.8–1.9 (m, 11 H), 1.52 (overlapping d, 2 H, α-CH), 5.81 (s, 10 H, Cp); ^{13}C NMR (C_6D_6) δ 26.8, 27.4, 37.2, 46.0, 82.5, 115.5. Yields of ~90% by ^{1}H NMR based on integration with respect to an internal standard (1,2-dichloroethane) with no other products observed. The cyclized products were spectroscopically identical with the independently prepared authentic compounds.[7a]

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