In order for the above chemistry to have practical application, the alkene complex diastereomers must equilibrate without significant epimerization at rhenium. Thus, optically active **1** was prepared from (+)-(*S*)-(η^5-C_5H_5)Re(NO)(PPh_3)(CH_3).[11] Addition of allylbenzene and propene gave mixtures of (*RR*)-**2a**BF_4^-/(*RS*)-**3a**BF_4^- and (*RR*)-**2c**BF_4^-/(*RS*)-**3c**BF_4^- with $[\alpha]_{589}^{23}$ of 86° and 115°. These were assumed to be optically pure,[6] and $[\alpha]_{589}^{23}$ for (*RR*)-**2a**BF_4^- (128°) and (*RS*)-**3a**BF_4^- (65°) were estimated from a series of extraction-enriched samples.[12] Equilibration (95 °C, 10–13 h, C_6H_5Cl) gave (9 ± 2):(91 ± 2) (*RR*)-**2a**BF_4^-/(*RS*)-**3a**BF_4^- and (6 ± 2):(94 ± 2) (*RR*)-**2c**BF_4^-/(*RS*)-**3c**BF_4^- mixtures with $[\alpha]_{589}^{23}$ 58° and 84°. Hence, alkene complexes (*RS*)-**3**BF_4^- can be prepared in both high diastereomeric *and* enantiomeric purity.

Metal alkene complexes have a rich chemistry and can be elaborated to organic compounds in numerous ways, such as by stereospecific nucleophilic attack on the alkene face anti to the metal.[13] Hence, the methodology developed herein for the selective binding of one enantioface of monosubstituted alkenes should lead to useful applications in asymmetric organic synthesis.

Acknowledgment. We thank the NIH for support of this research.

Supplementary Material Available: Tables of data for new compounds,[8] crystallographic data, atomic coordinates, bond lengths and angles, and anisotropic thermal parameters for **2a**PF_6^- (12 pages); table of observed and calculated structure factors (15 pages). Ordering information is given on any current masthead page.

(11) Merrifield, J. H.; Strouse, C. E.; Gladysz, J. A. *Organometallics* **1982**, *1*, 1204.

(12) Complex (*RS*)-**3a**BF_4^- could not be crystallized from the (34 ± 2):(66 ± 2) (*RR*)-**2a**BF_4^-/(*RS*)-**3a**BF_4^- mixture. However, a $[\alpha]_{589}^{23}$ versus mol % plot gives $[\alpha]_{589}^{23}$ for each component; $[\alpha]_{589}^{23}$ = 86°, 80°, and 77° for (34 ± 2):(66 ± 2), (25 ± 2):(75 ± 2), and (20 ± 2):(80 ± 2) mixtures, respectively.

(13) (a) Rosenblum, M. *J. Organomet. Chem.* **1986**, *300*, 191. (b) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987; pp 409–415 and 826–847.

Synthesis and Confirmation of Structure of the Antheridium-Inducing Factor from the Fern *Anemia mexicana*

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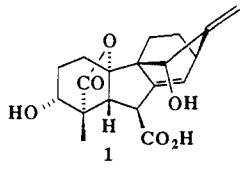
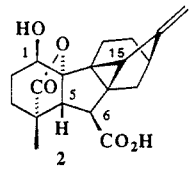
The structure of the antheridium-inducing factor from the fern *Anemia phyllitidus* has been established as **1** on the basis of structural studies undertaken by Nakanishi et al.[1] and a total synthesis of the racemate accomplished by Corey and Myers.[2] More recently, we have prepared **1** from gibberellin A_7.[3] A



1

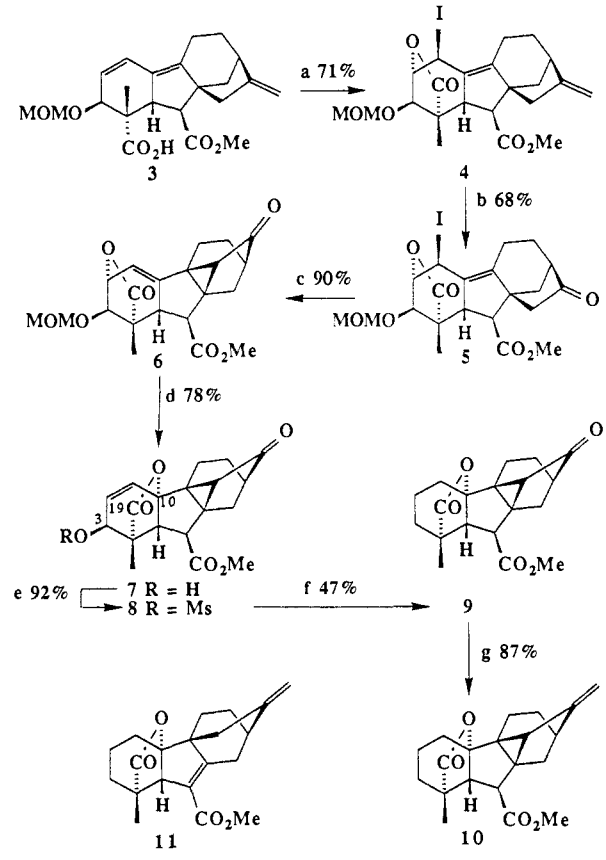


2

further antheridiogen has been obtained from the related species, *Anemia mexicana*,[4] for which structure **2** has been proposed on the basis of biogenetic considerations and minimal spectroscopic evidence.[5] Given the very considerable difficulties involved in the isolation of even microgram quantities of this new substance, there appeared to be little prospect of gathering further evidence for this formulation, and we accordingly embarked upon a synthesis of **2**. In this communication we describe the successful completion of this undertaking which has confirmed the tentative structural assignment and furnished adequate supplies of this new antheridiogen for the first time.

Before attempting the synthesis of **2**, we elected to prepare **10**[6] so that it might be possible to establish a set of reference spectra for the basic cyclogibberellane structure and verify the plausibility of formula **2**, especially the location of the hydroxy group in the 1β position.[7] The preparation of **10** is outlined in Scheme I, with the sequence as far as lactone **6** following closely the route taken earlier in our synthesis of **1**, except that this had commenced with the 3α-epimer of **3**.[3] Thus, diene acid **3** was converted into

Scheme I



[a] Reagents and conditions: (a) KI_3, K_2CO_3, THF–Et_2O–H_2O, 24 °C, 15 min; (b) O_3, Py, CH_2Cl_2, −78 °C; 5 s then Me_2S; (c) KH, THF, 0 → 24 °C over 45 min; (d) Ph_2BBr, CH_2Cl_2, −30 → −15 °C; (e) $MeSO_2Cl$, Et_3N, CH_2Cl_2, 0 °C, 6 h; (f) H_2, 5% Pd–$BaCO_3$, EtOAc, Py, 1 atm, 24 °C, 14 h; (g) CH_2Br_2, $TiCl_4$, Zn, CH_2Cl_2, 24 °C, 5 min.

(1) Nakanishi, K.; Endo, M.; Näf, U.; Johnson, L. F. *J. Am. Chem. Soc.* **1971**, *93*, 5579–5581. This factor has also been isolated from *A. hirsuta* (Zanno, P. R.; Endo, M.; Nakanishi, L.; Näf, U.; Stein, C. *Naturwissenschaften* **1972**, 512), *A. rotundifolia*, and *A. flexuosa* (Yamane, H.; Nohara, K.; Takahashi, N.; Schraudolf, H. *Plant Cell Physiol.* **1987**, *28*, 1203–1207).

(2) Corey, E. J.; Myers, A. G. *J. Am. Chem. Soc.* **1985**, *107*, 5574–5576. Corey, E. J.; Myers, A. G.; Takahashi, N.; Yamane, H.; Schraudolf, H. *Tetrahedron Lett.* **1986**, *27*, 5083–5084.

(3) Furber, M.; Mander, L. N. *J. Am. Chem. Soc.* **1987**, *109*, 6389–6396.

(4) Nester, J. E.; Veysey, S.; Coolbaugh, R. C. *Planta* **1987**, *170*, 26–33.

(5) Furber, M.; Mander, L. N.; Nester, J. E.; Takahashi, N.; Yamane, H., submitted for publication.

(6) This compound was also considered as a candidate for the structure of the less abundant but more potent antheridiogen from *Lygodium japonicum*. Cf. Yamane, H.; Takahashi, N.; Takeno, K.; Furuya, M. *Planta* **1979**, *147*, 251–256. Yamane, H.; Satoh, Y.; Nohara, K.; Nakayama, M.; Murofushi, N.; Takahashi, N.; Takeno, K.; Furuya, M.; Furber, M.; Mander, L. N., submitted for publication.

(7) Nomenclature and numbering based on the *ent*-gibberellane skeleton: *The Common and Systematic Nomenclature of Cyclic Diterpenes*, 3rd revision; Rowe, J. R., Ed., Forest Product Laboratory, U.S. Department of Agriculture: WI, 1968. The location of this group was based on the presence of a peak at *m/z* 116 in the mass spectrum of the derived trimethyl silyl ether methyl ester (Cf. Kirkwood, P. S.; MacMillan, J. *J. Chem. Soc., Perkin Trans. 1*, **1982**, 689–697) and on the assumption of anisotropic deshielding of H(5) and H(15) in the putative structure.

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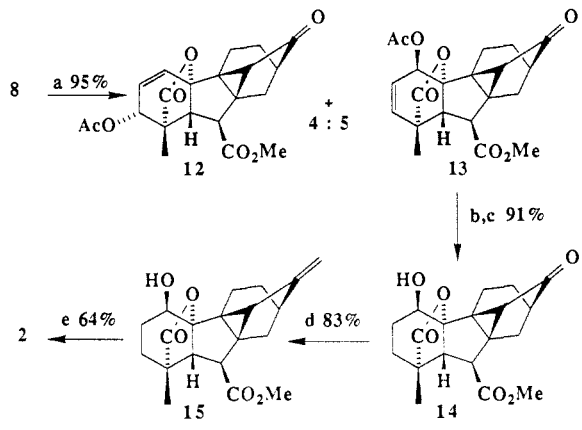
Scheme II



[a] Reagents and conditions: (a) LiOAc, HMPT, 4 °C, 72 h; (b) K_2CO_3, MeOH, 24 °C, 15 min; (c) H_2, Rh-Al_2O_3, EtOAc, 1 atm, 24 °C, 6 h; (d) CH_2Br_2, $TiCl_4$, Zn, CH_2Cl_2, 24 °C, 5 min; (e) *n*-PrSLi, HMPT, 24 °C, 1.5 h.

iodolactone **4**, mp 131-3 °C, $[\alpha]^{25}_D$ -370° (*c* 0.096),[8] which was ozonolyzed to norketone **5**, mp 131-3 °C, $[\alpha]^{25}_D$ -361° (*c* 0.088). Formation of the 9,15-cyclogibberellane skeleton was then effected by an intramolecular alkylation reaction mediated by potassium hydride, to afford **6**, mp 167-8 °C, $[\alpha]^{25}_D$ -153° (*c* 0.094). Subsequent reaction with diphenylboron bromide[9] not only removed the protecting group from the 3β-hydroxyl but also reestablished the desired A-ring/19β→10 lactone structure, thereby forming **7** [colorless oil, $[\alpha]^{25}_D$ -41° (*c* 0.023)]. Although the basis of this apparently contrathermodynamic isomerization[10] has not yet been elucidated, it appears to be general for this type of compound, and the saving of three steps greatly enhances the efficiency of these gibberellin to antheridiogen interconversions. Deletion of the functionality in ring A was effected by hydrogenolysis/hydrogenation of mesylate **8**, $[\alpha]^{25}_D$ +41° (*c* 0.016), following which, several attempts were made to convert the resulting ketone **9**, $[\alpha]^{25}_D$ -81° (*c* 0.006), into the target ester **10** by means of a Wittig reaction.[11] Although the formation of **11** (arising from a retrograde Michael reaction)[3] in addition to **10** came as no surprise, the recovery of ether soluble material was only ca. 20%.[12] The problem was satisfactorily resolved by employing the Lombardo modification[13] of the Oshima-Nozaki procedure,[14] which afforded **10** in 87% yield as a colorless oil, $[\alpha]^{21}_D$ -65° (*c* 0.008). Comparison of its ^{1}H NMR spectrum with that of the natural substance revealed a close correspondence in the chemical shifts associated with the respective methylene and H(6) resonances, but in conformity with expectations arising from earlier spectroscopic analyses,[5] the signals associated with H(5) and H(15) in **10** occurred at approximately 0.5 ppm higher field relative to the *A. mexicana* antheridiogen; i.e., assuming the same basic structure, the differences were consistent with the presence of a 1β-hydroxy function in the latter compound.

Confirmation of structure **2** for the new antheridiogen was established as outlined in Scheme II by treating mesylate **8** with lithium acetate in HMPT, which afforded a 4:5 mixture of the oily S_N2 and syn-S_N2' products **12** $[\alpha]^{21}_D$ -190° (*c* 0.012), and **13** $[\alpha]^{21}_D$ -280° (*c* 0.015), respectively.[15] Hydrolysis of the latter followed by hydrogenation gave hydroxy ketone **14**, mp 220-1 °C, $[\alpha]^{25}_D$ -103° (*c* 0.013), and thence the desired olefinic ester **15** as a colorless foam $[\alpha]^{21}_D$ -50° (*c* 0.003) by methylenation as before[13] (once again the Wittig reaction proved to be unsatisfactory). The trimethyl silyl ether of this product was identical by GC/MS with that of the methyl ester derived from natural material,[16] while the parent acid **2**, mp 213-4 °C, $[\alpha]^{21}_D$ -72° (*c* 0.013, MeOH), [derived by treatment of **16** with lithium propanethiolate in HMPT][17] afforded a virtually identical ^{1}H NMR spectrum with that obtained from an authentic sample.[16,18]

The availability of **2** by means of this synthesis will greatly expedite investigations into the biological role of this intriguing substance, while the discovery of yet a further skeleton for this class of phytohormones not only injects considerable further interest into the area but also provokes contemplation of a possible alternative hypothesis for the biosynthetic origin of **1** based on an analogue of **2**. The consolidation of the synthetic methodology and augmentation of the spectroscopic data base also enhances prospects for the elucidation of the structures possessed by further antheridiogens obtained from other ferns.[19]

Supplementary Material Available: Characterization data for compounds **10** and **15** (1 page). Ordering information is given on any current masthead page.

(8) All compounds were fully characterized by ^{1}H and ^{13}C NMR spectra, mass spectra, and HRMS. Optical rotations were measured in dichloromethane except where otherwise indicated.
(9) Guindon, Y.; Yoakim, C.; Morton, H. E. *J. Org. Chem.* **1984**, *49*, 3912-3920.
(10) Cf. Kirkwood, P. S.; MacMillan, J.; Sinnott, M. L. *J. Chem. Soc., Perkin Trans 1* **1980**, 2117-2121.
(11) Kirkwood, P. S.; MacMillan, J.; Beale, M. H. *J. Chem. Soc., Perkin Trans. 1*, **1982**, 699-706.
(12) This result indicated that little of the initial adduct had closed to the oxaphosphetane and proceeded to the normal product. It was possible to glean further amounts of **10** by heating the aqueous layer with DBU, however, suggesting that the missing material could be accounted for by the water soluble betaine.
(13) Lombardo, L. *Tetrahedron Lett.* **1982**, *23*, 4293-4296. The reagent was freshly prepared by stirring the components at 4 °C for 14 h before use.
(14) Oshima, K.; Takai, K.; Hotta, H.; Nozaki, H. *Tetrahedron Lett.* **1978**, 2417-2420.
(15) This reaction was first modelled on the structurally analogous gibberellin A_7 methyl ester 3-mesylate, following an earlier study conducted in buffered aqueous acetone (Duri, Z. J.; Hanson, J. R. *J. Chem. Soc., Perkin Trans 1* **1984**, 603-607). Under these conditions we obtained only a 20% yield of the desired 1β-substitution product, 20% of the 1α-adduct, and 43% of the 3α-isomer. However, the use of the dipolar aprotic solvent HMPT enhanced the yield of the 1β-isomer considerably; this improvement was readily transferred to the preparation of **13**.
(16) We gratefully acknowledge the cooperation of Dr. J. E. Nester, Professor N. Takahashi, and Dr. H. Yamane in providing spectroscopic data, and to Professor J. MacMillan and Dr. J. E. Nester for conducting ^{1}H NMR and GC/MS comparisons. The gibberellin substrates utilized in this project were generously donated by Abbott Laboratories and ICI Plant Protection.
(17) Bartlett, P. A.; Johnson, W. S. *Tetrahedron Lett.* **1970**, 4459-4462.
(18) The sample of the natural antheridiogen was not completely pure. Variations in the chemical shifts of some resonances with changes in concentration also complicated the comparison.
(19) Näf, W.; Nakanishi, K.; Endo, M. *Bot. Rev.* **1975**, *41*, 315-359.

Isotope Effects on Isotope Effects. Failure of the Rule of the Geometric Mean as Evidence for Tunneling[1]

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We showed in earlier work that secondary β-tritium isotope effects in eliminations from 2-arylethyl derivatives are often larger than expected on the basis of rehybridization of the C-H(T) bond from sp^3 to sp^2 as the system progresses along the reaction coordinate.[2-4] We suggested that a contribution of tunneling to the secondary isotope effect could be responsible for this discrepancy and presented calculations showing that a significant tunnel correction results when the bending motions of the non-

(1) This work was supported by the National Science Foundation.
(2) Subramanian, Rm.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1984**, *106*, 7887-7890.
(3) Saunders, W. H., Jr.; Price, R. C.; Subramanian, Rm. In *Physical Organic Chemistry 1986*; Kobayashi, M., Ed.; Elsevier: Amsterdam, 1987; pp 197-202.
(4) Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1985**, *107*, 164-169.

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