per-containing proteins (ca. 10^5–10^6 M^{-1} s^{-1}) or low molecular weight complexes with bidentate or polydentate ligands (10^2–10^7 M^{-1} s^{-1}). Indeed, only water as a ligand is reported to show a self-exchange rate constant significantly smaller than this upper limit. One possibility for the small value of k in the present system is the lack of an effective orbital pathway coupling the unpaired electron in the Cu(II) $d_{x^2-y^2}$ orbital to the appropriate electron donor oribtal in the Cu(I) complex.

Acknowledgment. This research was supported by the NSF (Grant CHE 84-17548), the David and Johanna Busch Foundation, and the NIH (Instrumentation Grant 1510 RRO 1486 O1A). We thank Dr. R. Mobashar for help with the electrochemical measurements and Profs. S. Isied, E. Solomon, and A. M. Yacynych for helpful discussions. We thank Dr. B. Toby for help in constructing the digitized EPR data aquisition system, J. Bumby for assistance in measuring and simulating EPR spectra, and J. Westbrook for local revisions of the EPR simulation program that was furnished by the Illinois ESR Research Center, NIH Division of Research Resources Grant No RR01811.

Note Added in Proof. Reduced coupling of the Cu(II) d vacancy to the imidazole ligands in another pseudotetrahedral complex, Cu(II)-doped $ZnCl_2$-(1,2-dimethylimidazole)$_2$, has been observed by single-crystal EPR studies (Gewirth, A. A.; Cohen, S. L.; Schugar, H. J.; Solomon, E. I. *Inorg. Chem.* **1987**, *26*, 1133) and by single-crystal electron spin-echo envelope modulation studies (Colenari, M. J.; Potenza, J. A.; Schugar, H. J.; Peisach, J., submitted for publication). This latter study reveals that the SHF coupling constants of both the directly ligated and remote imidazole nitrogens are approximately half of those exhibited by planar Cu(II) tetraimidazole complexes.

Supplementary Material Available: Tables of atomic coordinates, anisotropic and isotropic thermal parameters, and bond distances and angles for **5–8** (39 pages); observed and calculated structure factors for **5–8** (86 pages). Ordering information is given on any current masthead page.

A Total Synthesis of Racemic Paulownin Using a Type II Photocyclization Reaction

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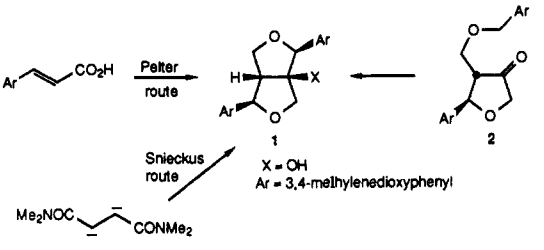
Abstract: The lignan paulownin was prepared in a seven-step route from piperonal. The key step was a type II photocyclization reaction wherein two of the four stereogenic centers were introduced.

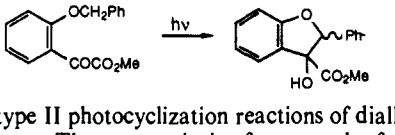
Photochemical reactions have been employed for the construction of a wide range of natural products.[1] Smith,[2] Crimmins,[3] and Winkler[4] have made effective use of the 2 + 2 cycloaddition reaction for the synthesis of terpenes and alkaloids. Mariano[5] has studied electron transfer cyclizations of amino ketones, providing novel strategies for the synthesis of fused and spirocyclic compounds. Schultz[6] has harnessed the photochemical rearrangements of cyclohexadienones, generating clever and direct syntheses of cyclopentenones and other useful synthetic intermediates. In contrast, the hydrogen atom abstraction–cyclization chemistry, often termed the type II photocyclization, has been almost unused in natural products synthesis. One notable exception is the elegant use of this reaction by Paquette to create the cyclobutane ring in punctatin.[7] Photoenolization, a related reaction, has been used by Oppolzer and others for alkaloid synthesis.[8] In this article we report the first total synthesis of paulownin,[9] a novel lignan. The key step in the synthesis is a type II photocyclization for the stereoselective formation of one of the heterocyclic rings.

The photophysical basis of the type II photocyclization reaction has been well studied, most notably by Wagner and Scaiano.[10]

Scheme I



They have demonstrated that an n–π^* triplet state is involved in the type II photocyclizations of diaryl and aryl alkyl ketones. They also reported that subtle conformational effects can profoundly influence product distributions. The type II photocyclization reactions of aryl glyoxylates have been rigorously examined by Pappas[11] and by Lappin[12] (eq 1). Pappas discovered a dramatic solvent effect on the stereochemistry of the cyclization.



(1)

Studies of type II photocyclization reactions of dialkyl ketones are less common. The vast majority focus on the formation of cyclobutanols.[13] Indeed, unless the 1,5-hydrogen atom abstraction pathway is blocked, it will be the predominant one. Paquette made

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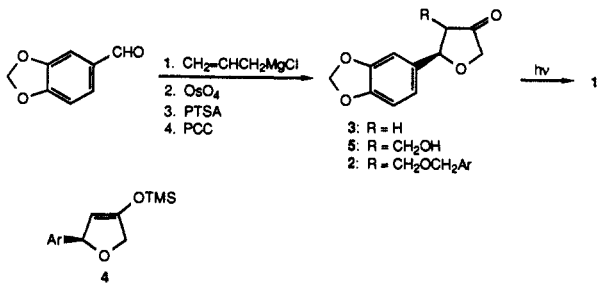
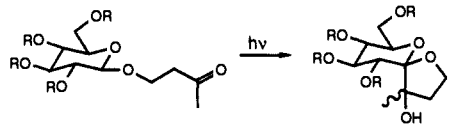
Scheme II

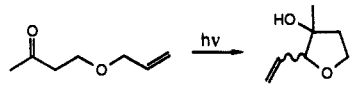


good use of 1,6-hydrogen atom abstraction reactions in the latter stages of his classic synthesis of dodecahedrane.[14] A limited study of five-membered ring formation was made by Descotes[15] (eq 2).



(2)

His studies, which dealt largely with carbohydrate systems, showed that such cyclizations generally afforded stereoisomeric mixtures of tetrahydrofuranols. Additionally, Carless and co-workers noted the following cyclization:[16]



(3)

Despite the poor stereoselectivity observed in the acyclic systems described above, we felt that stereoselectivity could be improved if the type II photocyclization was used to append a ring onto a rigid ring system. The furo[3,4-*c*]furan ring system of the lignans was chosen as a test case. Not only does this ring system pose the challenge of creating four contiguous stereogenic centers but there are also several members of this lignan family which exhibit biological activity.

The structure of paulownin (**1**) is shown in Scheme I and is representative of this class of lignans. Most members of this class have two identical aryl rings. Four basic strategies have been successfully employed to synthesize the furo[3,4-*c*]furan lignans. One strategy[17] is exemplified by a creative synthesis by Snieckus and features the reaction of 2 equiv of an aldehyde with a succinamide dianion. The resulting dihydroxydiamide was then cyclized under acidic conditions and converted to a lignan. This process is extremely direct. However, the production of diastereomeric mixtures and elimination products in the cyclization step is a drawback. A second strategy was developed by Pelter and co-workers.[18] It involved the dimerization of a substituted cinnamic acid with thallium trifluoroacetate followed by lactone reduction and deoxygenation. The third strategy, the Whiting strategy, featured the intramolecular cyclization of the enol silyl ether of a lactone.[19] Finally, an enantiocontrolled route centered around an intramolecular Diels–Alder reaction has recently been reported.[20]

Our strategy is quite different from the previous approaches. It requires the preparation of ketone **2**, which in turn would be constructed from piperonal. We anticipated that the photocyclization would generate a cis ring fusion and that the diradical intermediate in the photocyclization reaction would be more stable with the aryl group on the developing exo face.

The ketone **3** was easily synthesized in 49% overall yield from piperonal by reaction with allylmagnesium bromide followed by osmium tetraoxide hydroxylation, acid-mediated triol cyclization,[21] and PCC oxidation (Scheme II). Originally, we envisioned that **2** would be prepared by the reaction of enol silyl ether **4** with the appropriate chloromethyl alkyl ether. We reasoned that the predominant kinetic enolate produced by the reaction of **3** with lithium diisopropylamide (LDA) would be derived from deprotonation of the methylene not adjacent to the oxygen of the tetrahydrofuran ring. The reaction of **4** and chloromethyl benzyl ether did not produce ketone **2** (Ar = Ph) despite several variations in Lewis acid and temperature. Fortunately, the enolate prepared from **3** and LDA reacted with gaseous formaldehyde to afford hydroxy ketone **5** in 50% yield. The 10.2-Hz coupling constant for the benzylic methine proton indicated that the aryl and hydroxymethyl groups were trans. Ketone **2** was then produced in 42% yield by using the trichloroimidate methodology developed by Wesse.[22]

The type II photocyclization was conducted in a quartz tube at ambient temperature with a medium-pressure Hanovia lamp. The reaction was complete on a millimole scale in less than 1 h. In practice, the reaction was run to approximately 90% completion and the product separated from **2** by silica gel chromatography. Our racemic bicyclic alcohol **1** was identical with natural palownin by proton NMR and ^{13}C NMR.[23] Significantly, **1** was the *only* product, as evidenced by TLC and liquid chromatographic analysis of the solution directly after photolysis. The origin of this high kinetic stereoselectivity is at present unclear.

The synthetic utility of the type II photocyclization reaction has been demonstrated by a stereoselective total synthesis of racemic paulownin. The synthesis proceeds in only seven steps from piperonal. The high stereoselectivity observed when the type II photocyclization is conducted on a cyclic compound should make this reaction quite attractive to synthetic organic chemists.

Experimental Section

Unless otherwise noted, materials were obtained from commercial suppliers and were used without purification. H:EA refers to hexanes–ethyl acetate solvent mixtures for TLC and chromatography. The purity of all title compounds was determined to be >90% by proton NMR and/or elemental analysis.

1-(1,3-Benzodioxol-5-yl)-3-buten-1-ol. To a solution of piperonal (4.50 g, 30 mmol) in 60 mL of THF at 0 °C was added allylmagnesium bromide (1 M, 31 mL, 31 mmol). The solution was allowed to warm slowly to ambient temperature over 2 h. The solution was poured into water and extracted twice with methylene chloride. The combined organic layers were dried and concentrated in vacuo. The residue was purified by flash chromatography on silica gel with 5:1 H:EA to afford 5.13 g (89.1% yield) of alcohol. The alcohol was a clear liquid. NMR ($CDCl_3$): δ 2.01 (d, J = 2.7 Hz, 1 H), 2.47 (t, J = 6.9 Hz, 2 H), 4.65 (dt, J = 2.7, 6.9 Hz, 1 H), 5.10–5.20 (m, 2 H), 5.79 (ddt, J = 6.9, 9.6, 17.4 Hz, 1 H), 5.95 (s, 2 H), 6.75–6.87 (m, 3 H). IR (film): 3390, 3065, 2890, 1635, 1605, 1500, 1485, 1440, 1240, 1035, 925, 810 cm^{-1}. TLC (2:1 H:EA): R_f = 0.36. MS: 65, 93, 115, 149, 174.

5-(1,3-Benzodioxol-5-yl)tetrahydrofuran-3-one (3). To a solution of 1-(1,3-benzodioxol-5-yl)-3-buten-1-ol (2.67 g, 13.9 mmol) in 70 mL of 8:1 acetone–water was added *N*-methylmorpholine *N*-oxide (1.95 g, 16.7 mmol) followed by osmium tetraoxide (3.5 mL of tBuOH solution, 0.69 mmol). The solution was stirred for 23 h at ambient temperature. The reaction was quenched by 2.20 g of sodium thiosulfate and 2.20 g of Florisil. The suspension was stirred for 30 min and filtered through silica gel with ethyl acetate. The organic layer was dried and concentrated in vacuo to provide 2.8 g of a sticky liquid which was taken on to the next step.

To a solution of the triol (2.8 g) in 250 mL of chloroform was added *p*-toluenesulfonic acid (0.500 g). The solution was stirred at 50 °C for

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12 h. The solvent was removed in vacuo to yield a light yellow oil. To a suspension of PCC (4.38 g, 20 mmol) and Florosil (4.5 g) in 40 mL of anhydrous methylene chloride at −10 °C was added the alcohol (12.7 mmol). The suspension was allowed to slowly warm to ambient temperature over 20 h. The suspension was filtered through silica gel with 2:1 H:EA. The filtrate was concentrated to afford a residue. This residue was purified by flash chromatography on silica gel with 9:1 H:EA to afford 1.68 g (57% yield) of ketone **3**. This compound was a white solid with mp 70–71 °C. NMR ($CDCl_3$): δ 2.50 (dd, J = 9.6, 18 Hz, 1 H), 2.81 (dd, J = 6.0, 18 Hz, 1 H), 3.98 (d, J = 17.1 Hz, 1 H), 4.22 (d, J = 17.1 Hz, 1 H), 5.19 (dd, J = 6, 9.6 Hz, 1 H), 5.79 (s, 2 H), 6.79–6.90 (m, 3 H). IR (CH_2Cl_2): 1755, 1500, 1440, 1250, 1050, 1035, 940, 810, 735 cm^{-1}. MS: m/z 89, 135, 147, 148, 163, 176, 206. HRMS: calcd for $C_{11}H_{10}O_4$ 206.0579, found 206.0577. TLC (3:1 H:EA): R_f = 0.46.

5-(1,3-Benzodioxol-5-yl)-4-(hydroxymethyl)tetrahydrofuran-3-one (5). To a solution of lithium diisopropylamide (prepared from 2.1 mmol of diisopropylamine and 2.0 mmol of *n*-butyllithium) in 4 mL of THF at −78 °C was added ketone **3** (0.412 g, 2.0 mmol) in 1 mL of THF. The solution was stirred at −78 °C for 30 min, and gaseous formaldehyde (prepared by heating 20 mmol of paraformaldehyde at 150 °C with a nitrogen stream) was introduced into the solution. The reaction was quenched with acetic acid (0.25 g, 4.1 mmol). Methylene chloride and water were added. The organic layer was washed with brine, dried, and concentrated. The residue was purified by flash chromatography on silica gel with 2:1 H:EA to provide 0.169 g (50%) of hydroxy ketone **5**. NMR ($CDCl_3$): δ 2.02 (bt, J = 3 Hz, 1 H), 2.44–2.53 (m, 1 H), 3.95–4.05 (m, 1 H), 3.97 (d, J = 17 Hz, 1 H), 4.36 (d, J = 17 Hz, 1 H), 5.02 (d, J = 10.2 Hz, 1 H), 5.98 (s, 2 H), 6.79–6.96 (m, 3 H). IR ($CHCl_3$): 3460, 2878, 1750, 1485, 1440, 1245, 1035, 905, 730 cm^{-1}. TLC (2:1 H:EA): R_f = 0.22.

5-(1,3-Benzodioxol-5-yl)-4-[(1,3-benzodioxol-5-ylmethoxy)methyl]-tetrahydrofuran-3-one (2). To a solution of hydroxy ketone 3 (0.130 g, 0.55 mmol) and 1,3-benzodioxol-5-ylmethyl trichloroacetimidate (0.356 g, 1.20 mmol) in 5 mL of methyene chloride at ambient temperature was added a crystal of camphorsulfonic acid. The solution was stirred for 44 h. The solution was diluted with brine and was extracted twice with ether. The organic layer was dried and concentrated. The residue was purified by chromatography on silica gel with 10:1 H:EA to provide 0.075g (42% yield) of **2**. Ketone **2** was a viscous oil. NMR ($CDCl_3$): δ 2.41–2.43 (m, 1 H), 3.50 (dd, J = 3.3, 9.6 Hz, 1 H), 3.83 (dd, J = 3.3, 9.6 Hz, 1 H), 3.97 (d, J = 17.1 Hz, 1 H), 4.31 (d, J = 17.1 Hz, 1 H), 4.32 (d, J = 11.7 Hz, 1 H), 4.43 (d, J = 11.7 Hz, 1 H), 5.11 (d, J = 9.9 Hz, 1 H), 5.95 (s, 2 H), 5.96 (s, 2 H), 6.70–6.86 (mm, 6 H). IR ($CHCl_3$): 2880, 1754, 1485, 1440, 1245, 1035, 905, 725 cm^{-1}. MS: m/z 77, 135, 149, 205, 218, 235, 260, 370. HRMS: calcd for $C_{20}H_{18}O_7$ 370.1053, found 370.1049. TLC (3:1 H:EA) R_f = 0.35.

Paulownin (1). A solution of **2** (0.030 g, 0.081 mmol) in 20 mL of benzene was degassed with argon. The solution was irradiated with a medium-pressure Hanovia lamp for 1 h. The solution was concentrated. The residue was purified by chromatography on silica gel with 5:1 H:EA to afford 0.0165 g (68% based on recovered **2**) of **1**. Alcohol **1** was a white solid with mp 82–85 °C. Both the proton NMR and the ^{13}C NMR were identical with those reported in the literature. NMR ($CDCl_3$): δ 1.62 (s, 1 H), 3.04–0.06 (m, 1 H), 3.83 (dd, J = 6.3, 9 Hz, 1 H), 3.91 (d, J = 9.3 Hz, 1 H), 4.04 (d, J = 9.3 Hz, 1 H), 4.51 (dd, J = 8.1, 9 Hz, 1 H), 4.82 (s, 1 H), 4.84 (d, J = 5.1 Hz, 1 H), 5.96 (s, 2 H), 5.98 (s, 2 H), 6.78–6.94 (m, 6 H). ^{13}C NMR ($CDCl_3$): 60.40, 71.63, 74.76, 85.77, 87.47, 91.65, 101.10, 101.23, 106.87, 107.37, 108.19, 108.57, 119.77, 120.07, 129.21, 134.56, 147.24, 147.98. IR ($CHCl_3$): 3430, 1490, 1435, 1245, 900, 730 cm^{-1}. MS: m/z 69, 77, 93, 103, 135, 149, 163, 205, 220, 235, 370. HRMS: calcd for $C_{20}H_{18}O_7$ 370.1053, found 370.1052.

Acknowledgment. We thank the Herman Frasch foundation for support of this research.

Registry No. (±)-**1**, 121123-82-8; (±)-**2**, 125783-25-7; (±)-**3**, 125783-22-4; (±)-**5**, 125783-23-5; piperonal, 120-57-0; (±)-1-(1,3-benzodioxol-5-yl)-3-buten-1-ol, 42337-03-1; 1-(1,3-benzodioxol-5-yl)-1,3,4-butanetriol, 125783-20-2; 5-(1,3-benzodioxol-5-yl)tetrahydrofuran-3-ol, 125783-21-3; 1,3-benzodioxol-5-ylmethyl trichloroacetimidate, 125783-24-6.

The Vinylogous Anomeric Effect in 3-Alkyl-2-chlorocyclohexanone Oximes and Oxime Ethers

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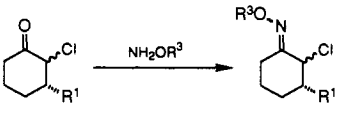
Contribution from the Roger Adams Laboratory, Department of Chemistry, University of Illinois, Urbana, Illinois 61801. *Received October 10, 1989. Revised Manuscript Received December 7, 1989*

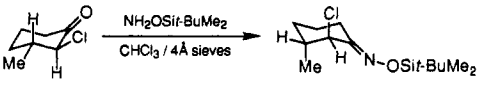
Abstract: A series of *trans*-3-alkyl-2-chlorocyclohexanones, **2** (methyl, ethyl, isopropyl, and *tert*-butyl), have been prepared and shown to exist predominantly in the diequatorial chair conformation except the *tert*-butyl derivative which prefers a twist-boat. Formation of the oximes and various oxime derivatives (methyloxime, silyloxime) results in a remarkable conformational inversion for the methyl, ethyl, and isopropyl systems. By analysis of vicinal interproton coupling constants it is believed that these compounds exist predominantly in the diaxial chair conformation. This is corroborated by an X-ray crystal structure of (*E*)-*trans*-**5a** which shows that the chair with diaxial substituents is indeed preferred in the solid state. A strong hyperconjugative stabilization of the axial conformation is proposed to be the origin of this preference which is termed the *vinylogous anomeric effect*.

The anomeric effect (and its generalized manifestations) is well recognized as an important contributor to ground-state conformational analysis of heteroatom-containing systems.[1] The value of considering these same effects in reaction mechanisms (kinetic anomeric effect[2]) has also been amply demonstrated. Although

Scheme I



Scheme II



interpretations of the *origin of the effect* differ, the experimental facts are clear that electronegative groups prefer the axial orientation at the anomeric position of tetrahydropyrans. The

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