Table I. Copper(I)-Catalyzed Photobicyclization of Homoallyl Vinyl Ethers

<table>
<thead>
<tr>
<th>Entry</th>
<th>Vinyl Ether 1</th>
<th>Irradiation Time (h)</th>
<th>Product 2</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
<td>16</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>40</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>c</td>
<td></td>
<td>58</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>d</td>
<td>R = H, n = 5</td>
<td>24</td>
<td></td>
<td>92</td>
</tr>
<tr>
<td>e</td>
<td>R = CH₃, n = 5</td>
<td>24</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>f</td>
<td>R = H, n = 6</td>
<td>18</td>
<td></td>
<td>48</td>
</tr>
</tbody>
</table>

Table II. Synthesis of Multicyclic Butyrolactones by Selective Oxidation of Tetrahydrofuran Derivatives with Ruthenium Tetraoxide

<table>
<thead>
<tr>
<th>Entry</th>
<th>Hydroxyolefin Precursor</th>
<th>Ether 2 (X = H₂)</th>
<th>Oxidation Product 3 (X = O)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>H₂O₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>R = H, n = 5</td>
<td>80</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>e</td>
<td>R = CH₃, n = 5</td>
<td>8</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>f</td>
<td>R = H, n = 6</td>
<td>14</td>
<td></td>
<td>85</td>
</tr>
<tr>
<td>g</td>
<td>m = 5</td>
<td>4</td>
<td></td>
<td>73</td>
</tr>
<tr>
<td>h</td>
<td>m = 8</td>
<td>170</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>i</td>
<td>R¹ = CH₃, R² = H</td>
<td>1</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>j</td>
<td>R¹ = n-C₆H₄, R² = CH₃</td>
<td>120</td>
<td></td>
<td>83</td>
</tr>
<tr>
<td>k</td>
<td>see text</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The original alcohol substituent. Similar annihilations from allylic alcohols via unsymmetrical diallyl ethers are demonstrated by Table II entries g-j. The requisite diallyl ethers for photoannulation of 2g-j are readily available by Williamsson synthesis from the hydroxy olefin precursors indicated. It is noteworthy that the stereochemistry of the substituent R¹ in 3i and 3j is exclusively exo. This synthetically valuable stereocontrol is in sharp contrast with a topologically different previous synthesis of 3i by intermolecular photocyclodaddition of ethylene with 4, which affords an equal yield of the endo-epimer 5 (eq 3). The requisite diallyl ether 6 for photoannulation of 2k was prepared from cyclohexene oxide and allyl alcohol according to eq 4. Other synthetically useful transformations of the photoproducts 2 as well as copper(I)-catalyzed photocyclizations of unsaturated ethers incorporating additional functionality are under investigation and will be described in a full account.

Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, and to the National Science Foundation for support of this research. We thank Professors L. A. Paquette and H. Uda for copies of 'H NMR spectra of 2a and of 3i and 5, respectively.

(16) A discussion of the mechanistic basis of this stereoselectivity is deferred to a future full paper.


Conrotatory Ring Opening of Cis-Fused 3-Aminocyclobutenes. X-ray Analysis of a cis,trans-2H-Thiocin

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The thermal valence isomerization of (hetero) cyclobutenes to (hetero) 1,3-butadienes is a classic example of a stereospecific reaction, the conrotatory mode of which is in agreement with the principle of conservation of orbital symmetry in electrocyclic reactions. A large amount of work has been carried out on the thermal isomerization of compounds in which the cyclobutene moiety is cis annulated to another ring system. It is generally accepted that when the annulated ring possesses less than eight atoms, ring opening must occur by way of the symmetry-forbidden disrotatory mode or by homolytic or heterolytic pathways, all


having a higher activation energy. Epiti6 has predicted that the activation energy of the ring opening will be reduced by asymmetric substitution of the cyclobutene, as experimentally observed for 3-aminocyclobutenes cis fused to 5-, 7-, 8-, and 12-membered rings. On the basis of configurational interaction analysis he concluded that in these cases the disrotatory process will occur. In this communication we report experimental evidence to prove that the ring opening of cis-fused 3-aminocyclobutenes proceeds in a conrotatory mode.

As part of our work on the mechanism of the reaction of enamines with dimethyl acetylenedicarboxylate (DMAD),7 we synthesized cis-fused 3-aminocyclobutenes, a number of which have been reported previously. However, in our hands the reaction of DMAD and 1-(1-cyclohexen-1-yl)pyrrolidine (1a) in diethyl ether as described by Brannock et al.8 did not give the dimethyl 1-(1-pyrrolidinyl)bicyclo[4.2.0]octa-7-ene-1,2-dicarboxylate (2a) as a pure compound. Instead we obtained a mixture of two compounds that are interconverting at room temperature as indicated by 1H NMR spectroscopy. One of the compounds, showing a singlet absorption at 6 3.30 (OCH3, 3H) and a doublet absorption at 6 4.30 in its 13C NMR spectrum, could be identified as the [2 + 2] cycloadduct 2a. The other component, the amount of which increases in the mixture by lowering the temperature,9 shows a doublet of a doublet at 6 5.51 (J = 5.1 and 12.0 Hz, corresponding to 3H, 3H). After the mixture stood for some hours in CDCl3 at room temperature, however, its 1H NMR spectrum had changed dramatically and showed among others the absorptions of two valence isomers, viz., the [2 + 2] cycloadduct 2a and dimethyl 3-(1-pyrrolidinyl)-2,8-cyclooctadiene-1,2-dicarboxylate (4a).10 Therefore, we concluded that the reaction product of 1a and DMAD consisted of a mixture of two valence isomers, viz., the [2 + 2] cycloadduct 2a and dimethyl 3-(1-pyrrolidinyl)-cis-trans-2,8-cyclooctadiene-1,2-dicarboxylate (3a).

Prolonged reaction time resulted in the isomerization of the cis,trans diene to the thermodynamically more stable cis,cis-isomer 4a. Conclusive evidence for the cis,cis,cycloalkadiene structure 3 was obtained when we reacted 1-(3,6-dihydro-2H-thiopyrano[3,4-b]pyrrolizine-9-acetic acid, dimethyl ester [1H NMR (CDCl3) 4.43 (dd, J = 6, 10 Hz, 1H, N-Ch)]; 3.32 and 2.51 (ABq, J = 17.6 Hz, 2H, CH2)]. This result shows that there exists an equilibrium between 2b and 3b, though at ambient temperature 2b could not be detected by 1H NMR spectroscopy. The conversion of 3-aminocyclobutenes into pyrrolizines has been reported previously.11

Figure 1. Stereoscopic view of 3b.
Asymmetric hydroboration of prochiral alkenes with monoisopinocampheyloborane in the molar ratio of 1:1, followed by a second hydroboration of nonprochiral alkenes with the intermediate dialkyloboranes, provides the chiral mixed trialkyloboranes. Treatment of these trialkyloboranes with acetaldheyde under mild conditions results in the selective, facile elimination of the 3-pinanyl group, providing the corresponding chiral boronic acid esters with enantiomeric purities of 73–100% ee. Treatment of these intermediate with base and dichloromethyl methyl ether provides the chiral ketones, following oxidation of the intermediates, with enantiomeric purities as high as 90%.

The asymmetric synthesis of ketones has been extensively studied in the last decade. The activity, however, is achieved primarily by the enantioselective alkylation of appropriate ketones. In the case of an enantioselective alkylation of acyclic ketones, the most favorable results are realized only in the alkylation of symmetrical ketones, thereby limiting seriously the generality of the method. The present study reports a new, more general approach for the asymmetric synthesis of acyclic ketones involving asymmetric hydroboration–carbenoidation, as well as the first general synthesis of chiral boronic acid esters.

Asymmetric hydroboration has now been known for more than 2 decades, and many applications of the reaction have been reported. However, the high asymmetric induction achieved in the reaction has not hitherto been utilized for the asymmetric formation of carbon–carbon bonds. It is known that under vigorous conditions trialkyloboranes react with benzaldehyde to form the boronic acid esters. Recently this reaction has been applied for a direct chiral synthesis of boronic esters. However, the selective reaction of aldehydes with mixed trialkyloboranes is not known.

Consequently, the strategy of the present method depends upon the successful synthesis of chiral mixed trialkyloboranes, followed by selective elimination of the starting chiral auxiliary, the 3-pinanyl group, from the boron intermediate. Thus, hydroboration of trans-2-butene with monoisopinocampheyloborane$^{22}$ [IpcBH$_2$] in the molar ratio of 1:1 results in the formation of 3-pinanyl-2-butyloborane, which then rapidly hydroborates 1-pentene at $-25^\circ$C to provide the corresponding chiral mixed trialkyloborane.

**General Synthesis of Chiral Boronic Acid Esters.**

**Asymmetric Synthesis of Acyclic Ketones via Asymmetric Hydroboration–Carbenoidation**

Herbert C. Brown,* Prabhakar K. Jadhav, and Manoj C. Desai

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Received August 4, 1982

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**Supplementary Material Available:**

Tables of atomic positional and thermal parameters, interatomic distances and angles, and a list of observed and calculated structure factors (30 pages).

Ordering information is given on any current masthead page.

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