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Preparation of Highly Substituted Tetrahydropyrans via a Metal Assisted Dipolar Cycloaddition Reaction

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A range of highly substituted tetrahydropyrans have been prepared by reaction of a donor-acceptor cyclobutane, where the donor is a metal-alkyne complex, with an aldehyde under Lewis acid conditions.

We have recently reported the use of dicobalt complexes in the formation of new carbon-heteroatom bonds through [3+2] cycloaddition reactions via a stabilized dipole intermediate. The initial work carried out made use of substituted cyclopropanes with a metal-alkyne complex to stabilize the Nicholas carbocation. More recently, we have also reported the use of an iron-dienyl template to facilitate a similar reaction. Cycloaddition reactions involving three-membered rings have been the subject of recent interest e.g. for the synthesis of tetrahydro-1,2-oxazines, pyridines, and tetrahydrofurans. Ghorai et al. recently reported related reactions for the synthesis of substituted imidazoline starting from aziridines and the synthesis of tetrahydropyrimidines using azetidines. More recently, they also report a S_{N}2 type nucleophilic ring opening followed by a [4+2] cycloaddition of the same azetidines with aldehydes and ketones. However the equivalent strategy using a cyclobutane ring has never been reported. We believe that the use of donor-acceptor cyclobutanes in cycloadditions would both be a novel and useful addition to synthetic organic chemistry.

We now report that a novel and efficient [4+2] cycloaddition reaction has been developed using cyclobutane as a masked dipole. We envisaged treating a substituted cyclobutane with a Lewis acid in order to open the four-membered ring and reveal a stabilized dipole (Scheme 2). The malonate motif stabilizes the carbanion and the cobalt-alkyne complex stabilizes the cation as a Nicholas cation. The dipole could then be trapped with a suitable dipolarophile to effect a cycloaddition reaction.

Scheme 1 Cyclobutane-dipole equilibrium.

The substituted propargylic cyclobutane was prepared via a four-step methodology in 74% overall yield. The hydroxyester 3 was prepared by simple Aldol chemistry, then reduced to the corresponding alcohol 4 using LiBH₄. The diol 4 was converted into the dibromide 5 using bromine and triphenylphosphine at 0°C (Scheme 2). This sequence was “chromatography-free” and achieved in excellent yield. After complete conversion of the alcohols into the corresponding bromides, the triphenylphosphine oxide side product was recrystallised thrice from cold petrol affording the dibromide 5 in a quantitative yield. Displacement of the two bromines with dimethyl malonate and sodium hydride afforded the desired cyclobutane 6 in 74% yield.

Scheme 2 Preparartion of the required donor-acceptor cyclobutane.
Scheme 3 [4+2] Cycloaddition reaction.

![Scheme 3](image)

Table 1 Conditions and yields of cycloaddition reaction.

<table>
<thead>
<tr>
<th>Aldehyde (R)</th>
<th>Product</th>
<th>Time</th>
<th>Yield</th>
<th>d.e.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂Et</td>
<td>7</td>
<td>17 h</td>
<td>58%</td>
<td>20%</td>
</tr>
<tr>
<td>CH₃</td>
<td>8</td>
<td>30 min</td>
<td>73%</td>
<td>23%</td>
</tr>
<tr>
<td>Ph</td>
<td>9</td>
<td>1 d</td>
<td>34%</td>
<td></td>
</tr>
<tr>
<td>4-CH₂Ph</td>
<td>10</td>
<td>10 min</td>
<td>64%</td>
<td>cis</td>
</tr>
<tr>
<td>2-CH₂Ph</td>
<td>11</td>
<td>1 h</td>
<td>47%</td>
<td>cis</td>
</tr>
<tr>
<td>PhCH=CH</td>
<td>12</td>
<td>1 h</td>
<td>82%</td>
<td>cis</td>
</tr>
<tr>
<td>PhCH=CCH₃</td>
<td>13</td>
<td>25 min</td>
<td>84%</td>
<td>cis</td>
</tr>
<tr>
<td>CH₂CH=CH</td>
<td>14</td>
<td>1 h</td>
<td>82%</td>
<td>cis</td>
</tr>
<tr>
<td>CH₂CH=CH=CH</td>
<td>15</td>
<td>1 h</td>
<td>51%</td>
<td>cis</td>
</tr>
<tr>
<td>4-CH₂OPh</td>
<td>16</td>
<td>15 min</td>
<td>85%</td>
<td>cis</td>
</tr>
<tr>
<td>4-PhOPh</td>
<td>17</td>
<td>2 h</td>
<td>65%</td>
<td>cis</td>
</tr>
<tr>
<td>2-C₄H₈O</td>
<td>18</td>
<td>10 min</td>
<td>95%</td>
<td>cis</td>
</tr>
<tr>
<td>2-C₄H₈S</td>
<td>19</td>
<td>15 min</td>
<td>73%</td>
<td>cis</td>
</tr>
<tr>
<td>2,4-(CH₃O)₂Ph</td>
<td>20</td>
<td>10 min</td>
<td>92%</td>
<td>cis</td>
</tr>
<tr>
<td>3,4-(CH₃O)₂Ph</td>
<td>21</td>
<td>10 min</td>
<td>92%</td>
<td>cis</td>
</tr>
</tbody>
</table>

Cycloaddition reactions were performed in dichloromethane at room temperature using catalytic amounts of Lewis acid under an inert atmosphere. We had expected the cyclobutane core would have the same reactivity as the cyclopropane we had examined previously, however, the use of boron trifluoride as the activating Lewis acid gave only a complex mixture of products. Instead we found that catalytic quantities of scandium triflate were the preferred additive. A range of aldehydes were then used to trap the dipole formed during the reaction as summarised in Table 1. No reaction was seen without complexation of the alkyne to cobalt hexacarbonyl. Our initial choice of trapping agent was ethyl glyoxylate, as an electron deficient aldehyde, since electron deficient aldehydes gave the best yields in the cyclopropane case. The two separable diastereoisomers of the corresponding tetrahydropyran adduct 7 were isolated in 58% yield with 20% d.e. after 17 hours. Acetaldehyde also afforded its corresponding tetrahydropyran 8 in a 73% yield with 23% d.e. in 30 minutes, however it was the only aliphatic aldehyde that afforded the desired cycloadduct.

On moving to aryl aldehydes, benzaldehyde surprisingly afforded only the cis-isomer of 9 in a moderate yield of 34% after 24 hours. Using conjugated and aromatic aldehydes such as cinnamaldehyde and anisaldehyde, only the cis-isomers were produced during the reaction (12 and 16) in 82% and 85% yield respectively, a trend that continued for other electron rich aldehydes, (e.g. 18, 20 and 21). In contrast, p-nitrobenzaldehyde gave only the complexed starting material 2, with no sign of the pyran. Thus there is a marked difference between the three- and four-membered ring dipole precursors:

5 our previous studies found that electron deficient aldehydes gave the best yields with the cyclopropane, but low diastereoselectivities. In contrast the cyclobutane gives significantly better yields with electron rich aldehydes, and for the first time, excellent stereocontrol.

40 To assess the effect of steric hindrance, a comparison was made between p-tolualdehyde and o-tolualdehyde. The p-substituted aldehyde afforded 10 in 64% yield after only 10 minutes while o-tolualdehyde gave 11 in only 47% yield after 1 hour.

45 All diastereoselectivities were confirmed by nOe experiments and, in addition, X-ray crystal structures were determined for 8, 10, 18 and 19 (see Fig. 1 for structure of tetrahydropyran 19 and ESI for those of the others).

Figure 1 X-ray crystal structure of tetrahydropyran 19.

The mechanism of the reaction is not yet known, but the results described above suggest that two different mechanisms are likely to occur whether the aldehyde is electron rich or poor. If the aldehyde is electron poor the reaction is very slow or does not proceed at all. In this case, we believe the highly electron deficient carbonyl is subject to attack first by the malonate carbanion (Scheme 4).

Scheme 4 Proposed mechanism for the cycloaddition with electron deficient aldehydes.

When electron rich or conjugated aldehydes are used, the oxygen of the carbonyl will attack the Nicholas carbocation first, through delocalization of π electrons. In this case the mechanism is not concerted, the carbon-oxygen bond can rotate to obtain the most stable conformation before trapping the carbocation which may explain why only the cis isomer is obtained (Scheme 5).
In summary, we have synthesized an alkynylcyclobutane in 74% yield over 4 steps. We report for the first time a formal [4+2] cycloaddition reaction using a cyclobutane as a dipole precursor, providing a new way for the synthesis of six-membered heterocycles in a diastereoselective fashion. A wide range of aldehydes was used as trapping reagents to form tetrahydropyrans in good yields (up to 95%) and with excellent diastereoselectivities in some cases. Further work is under way to expand the scope of this reaction. The importance of the area has been underlined by the recent report of a related carbocyclic version [4+2] cycloaddition.‡

Scheme 5 Proposed mechanism for the cycloaddition with electron rich aldehydes.

Notes and references