Appendix 2

Evaluation of ee by chiral GC and by $^1$H NMR with the chiral shift reagent Eu(hfc)$_3$.

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A. Chiral GC.

A cycloaddition of cyclopentadiene to methacrolein, in principle, yields four norbornene adducts: two diastereoisomers, namely exo-CHO-3 and endo-CHO-3, and two enantiomers, $R$ and $S$ for each diastereomer.

An achiral cycloaddition (no catalyst or an achiral Lewis acid) yields more exo diastereoisomer than endo (see the Table at the bottom of Fig. 1). Each diastereoisomer is a racemic mixture (50% $R$+50% $S$).

A chiral catalyzed cycloaddition preserves and enhances substantially the amount of the exo norbornene derivative, but also favors one enantiomer over the other.

\[ \text{exo-CHO-3} \]
\[ \text{endo-CHO-3} \]

<table>
<thead>
<tr>
<th>catalyst</th>
<th>solvent</th>
<th>temp</th>
<th>time</th>
<th>exo:endo</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>THF</td>
<td>RT</td>
<td>8h</td>
<td>5.6:1</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>BLn* (L-Tartaric acid)</td>
<td>CH$_2$Cl$_2$</td>
<td>-78 C</td>
<td>24 h</td>
<td>94:6</td>
<td>92.4%</td>
<td>7.6%</td>
</tr>
<tr>
<td>BLn* (D-Tartaric acid)</td>
<td>CH$_2$Cl$_2$</td>
<td>-78 C</td>
<td>24 h</td>
<td>92:8</td>
<td>11%</td>
<td>89%</td>
</tr>
</tbody>
</table>

**Fig. 1.** Cycloaddition of cyclopentadiene to methacrolein under uncatalyzed and chiral catalyzed conditions.

The chiral (Supelco ALPHADEX120$^2$; oven temperature isotherm of 65 °C) GC traces for a crude sample resulted from the uncatalyzed (**Fig. 2**) and Lewis acid chiral catalyzed conditions.

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2 Cyclodextrin (CD) is a chiral component in the stationary phase of a DEX capillary column. Cyclodextrins are cyclic oligomers of six or more molecules of D(+)-glucose linked through $\alpha$(1-4) glycosidic bonds. In
boron catalyzed cycloaddition of cyclopentadiene to methacrolein (Fig. 3 and Fig. 4) are:

Fig. 2. Chiral GC trace of the crude product mixture resulted from cyclopentadiene cycloaddition to methacrolein.

Fig. 3. Chiral GC trace of the crude product mixture resulted from the cyclopentadiene cycloaddition to methacrolein in the presence of the chiral boron catalyst synthesized from the D-tartaric acid precursor.

Fig. 4. Chiral GC trace of the crude product mixture resulted from the cyclopentadiene cycloaddition to methacrolein in the presence of the chiral boron catalyst synthesized from the L-tartaric acid precursor.

particular, $\alpha$-CD contains six residues of glucose. The size of the torus-shaped cavity is 4.7-5.2 Å. The stationary phase of the ALPHADEX120 is formed from 20% permethylated $\alpha$-CD in poly(35% phenyl/65% dimethylsiloxane).

3 Samples provided by Emilie, Michelle, Jeremy, Elisa, Kathryn (5.32-2002).
GC peak identification.

- GC/MS peaks at RT: 31.562, 32.474 and 37.141 min are due to exo- and endo-CHO-3, respectively, because all display in GC/MS a molecular ion at 136. Based on the relative peak intensities of CHO signals in 1H NMR, it is clear that the major diastereoisomer is exo-CHO-3. Therefore, the peaks corresponding to RT 31.562 min and 32.474 min are due to R and S exo-CHO-3, respectively.
- The earlier two peaks (26.650 min and 27.177 min) are due to the enantiomers of the cyclopentadiene dimer (molecular ion 132)!
- The peak at 22.493 min is due to the methacrolein dimer (molecular ion 140).

Asymmetric cycloadditions:

The enantiomeric excess (ee) is defined as follows:

$$ee(\%) = \frac{|I_R - I_S|}{I_R + I_S} \times 100$$

$I_R$ (or $I_S$) is the intensity (%) of the respective peak in the GC output. The Table from the bottom of Fig. 1, provides the actual ee values calculated for the cycloadditions carried out with the chiral boron catalyst resulted from the precursors of tartaric acids enantiomers.

When the chiral catalyst precursor is derived from the (2R,3R)-tartaric acid (natural), the Diels-Alder adduct exo-CHO-3 has the R configuration. The S enantiomer of the exo-CHO-3 is formed when the catalyst is derived from (2S,3S)-tartaric acid.

B. NMR with shift reagents

Enantiomers are not differentiated in the NMR spectrum: the probe is isotropic. However, diastereoisomers display different chemical shifts. Diastereoisomer complexes are formed by mixing the chiral shift reagent Eu(hfc)₃ (4), with a mixture of enantiomers of exo- and endo-CHO-3 (in CDCl₃ solution). Because the shift reagent 4 is a Lewis

![European tris[3-(heptafluoropropylhydroxymethylene) (+)-camphorate] Eu(hfc)₃ very hygroscopic](image)

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acid, the Eu$^{3+}$ coordinates$^5$ at the oxygen of CHO. Eu$^{3+}$ induces a spreading of the chemical shifts over a wider range of the spectrum according to the McConnell-Robertson$^6$ equation: $\Delta = K \frac{3 \cos \theta - 1}{r_i^3}$. $\Delta$ is the “pseudocontact shift”, $r_i$ and $\theta$ are defined in the figure:

Since the proton from the CHO is very close to Eu$^{3+}$, it is anticipated to experience a large pseudocontact shift, shown by the arrows in Fig. 5. There are two H NMRs presented in this figure. In the right, the undopped H NMR, in which the larger singlet at 9.69 ppm is assigned to exo-CHO and the smaller singlet at 9.40 ppm that is assigned to endo-CHO. After adding Eu(hfc)$_3$, all the CHO moved downfield and became split in a 1:1 ratio.

![Fig. 5](image-url)

**Fig. 5.** The displacement and split of CHO signals as result of added Eu(hfc)$_3$ to crude exo-CHO-3 and endo-CHO-3 resulted in the uncatalyzed cycloaddition of cyclopentadiene to methacrolein.

At this time, there are no available Lanthanide Induced Shift (LIS)-H NMR data from catalyzed experiments. We hope to get these results from the work done by the third rotation. As for the chiral GC, the enantiomeric excess results according to the

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$^5$ Eu$^{3+}$ is paramagnetic (4f$^6$) and has short electron-spin relaxation time ($<10^{-12}$ s). Therefore, it induces H NMR shifts without appreciable line broadening.

equation: \( ee = \frac{|I_R - I_S|}{I_R + I_S} \times 100(\%) \). \( I_R \) and \( I_S \) are the magnitude of the integrals of LIS induced aldehyde proton signals (for enantiomer \( R \) and \( S \)).