Department of Chemistry and Biochemistry, University of Bern

Topic review

Cobalt Catalysed Organic Reactions

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‘. . . we invite the attention of chemists to a class of salts which for beauty of form and color, and for abstract theoretical interest, are almost unequaled either among organic or inorganic compounds.’

Wolcott Gibbs and Frederick Genth
“Researches of the ammoniacobalt bases”
Ancient Egyptians used cobalt ores to color glass more than 1300 B.C.E. (piece of such glass found in the tomb of Pharaoh Tutankhamen).

Cobalt ores were also used to color Chinese pottery from the Tang (600–900 C.E.) and Ming (1350–1650 C.E.) dynasties.

Elemental cobalt was first isolated by the Swedish chemist Georg Brandt in 1735.

Espionage provided one of the earliest documented uses of cobalt compounds (invisible ink by the Paris-based American agent Silas Deane in 1776–1777).
A common oxidation state for simple compounds is +2, for coordination compounds +3.

Co(II) complexes: d⁷ electron configuration, generally six- or four-coordinated, often high spin, distorted octahedral or tetrahedral geometries.

Co(III) complexes usually have a d⁶ low-spin electronic configuration almost exclusively six-coordinated, with octahedral or distorted octahedral geometries.

Low oxidation state chemistry of cobalt is dominated by organometallic complexes containing C-donor ligands.

Vitamin B₁₂ contains five-coordinate Co(I) in a square pyramidal N₅ coordination environment.
Contents

- Pauson-Khand Reaction
- Hydroazidation and Hydrohydrazination
- Cyclizations:
  - Co(II)-Salen-Catalyzed Cyclopropanation
  - Co(II)-Porphyrin-Catalyzed Cyclopropanation
  - [6+2] Cycloaddition
- C-H-functionalization
- Formation of Unsymmetrical Biaryls
- Heck-Type Reaction
- Iodolactonization
Pauson-Khand Reaction

Caroline Scheuermann nee Taylor and Benjamin Ward *New J. Chem.* **2008**, *32*, 1850-1880
Hydration, Hydrohydrrazination, Hydroazidation

Hydrohydrazination

\[
\text{Entry} \quad \text{Alkene} \quad \text{Product} \quad \text{Yield (\%)}
\]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkene</th>
<th>Product</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\text{Me} \quad \text{OH} )</td>
<td>Boc\text{NNHBoc} \quad \text{Me} \quad \text{Me} \quad \text{OH}</td>
<td>73 (d.r. 1:1)</td>
</tr>
<tr>
<td>2</td>
<td>(\text{Me} \quad \text{C} = \text{O} )</td>
<td>Boc\text{NNHBoc} \quad \text{Me} \quad \text{Me} \quad \text{C} = \text{O}</td>
<td>76</td>
</tr>
<tr>
<td>3</td>
<td>(\text{Br} )</td>
<td>Boc\text{NNNBoc} \quad \text{Me} \quad \text{Me} \quad \text{Br}</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>(\text{Polymerized} )</td>
<td>Boc\text{NNNBoc} \quad \text{Me} \quad \text{Me} \quad \text{N}</td>
<td>&lt;5</td>
</tr>
<tr>
<td>5</td>
<td>(\text{Me} )</td>
<td>Boc\text{NNBoc} \quad \text{Me} \quad \text{N}</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>(\text{Ts} )</td>
<td>Boc\text{NNBoc} \quad \text{Me} \quad \text{N}</td>
<td>74</td>
</tr>
<tr>
<td>7</td>
<td>(\text{NHBoc} )</td>
<td>(\text{NHBoc} )</td>
<td>66</td>
</tr>
</tbody>
</table>

Key features

- High Markovnikov selectivity
- Strong activating effect of \(\alpha\)-phenyl
- Large functional group tolerance

Mechanism of Hydrohydrazination Reaction

Hydroazidation

$$R_1 R_2 + TsN_3 \xrightarrow{Co(BF_4)_2 \cdot 6H_2O, \text{ligand 37}} R_1 R_2 N_3$$

**Limitations**
- Substrate with stabilizing group in conjugation do not react
- Full conversion could not be obtained with di- and trisubstituted olefins

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkene</th>
<th>Product</th>
<th>Yield (%) PhSiH$_3$/TMDSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ph-CH=CH</td>
<td>Ph-CH$_3$CH$_3$N$_3$</td>
<td>90 / 86</td>
</tr>
<tr>
<td>2</td>
<td>O-O-CH=CH</td>
<td>O-O-CH$_3$CH$_3$N$_3$</td>
<td>65 / 62</td>
</tr>
<tr>
<td>3</td>
<td>Bn-CH=CH</td>
<td>Bn-CH$_3$CH$_3$N$_3$</td>
<td>35 / 39</td>
</tr>
<tr>
<td>4</td>
<td>Bn-CH=CH</td>
<td>Bn-CH$_3$CH$_3$N$_3$</td>
<td>75 / 77</td>
</tr>
<tr>
<td>5</td>
<td>Me-Me-Me</td>
<td>Me-Me-Me</td>
<td>89 / 76</td>
</tr>
<tr>
<td>6</td>
<td>t-BuPh$_2$SiO-CH=CH</td>
<td>t-BuPh$_2$SiO-CH$_3$CH$_3$N$_3$</td>
<td>63 / 48</td>
</tr>
</tbody>
</table>

Hydroazidation

\[
\text{entry} \quad \text{alkene} \quad \text{product} \quad \text{Yield}^a \quad \text{Yield}^b \quad \text{Yield}^c \\
1 \quad \text{Ph} = \text{Me} \quad \text{Ph} = \text{Me} \quad 86% \quad 94% \quad 91% \\
2 \quad t-\text{BuPh}_2\text{SiO} = \text{Me} \quad t-\text{BuPh}_2\text{SiO} = \text{Me} \quad 67% \quad 19% \quad 44% \\
3 \quad \text{Bn} = \text{Me} \quad \text{Bn} = \text{Me} \quad 39% \quad <20% \quad 28% \\
4 \quad t-\text{BuPh}_2\text{SiO} = \text{Me} \quad t-\text{BuPh}_2\text{SiO} = \text{Me} \quad 58% \quad 89% \quad 91% \\
5 \quad \text{Bn} = \text{Me} \quad \text{Bn} = \text{Me} \quad 40% \quad 64% \quad 76% \\
6 \quad t-\text{BuPh}_2\text{SiO} = \text{Me} \quad t-\text{BuPh}_2\text{SiO} = \text{Me} \quad 48% \quad 83% \quad 79%
\]

Mechanism of Hydroazidation Reaction

Hydrohydrazination and Hydroazidation for Amination

A: Hydrohydrazination

1) 8 M HCl, THF
2) Zn, HOAc, acetone
3) HCl, Et₂O

B: Hydroazidation

B1
1) CuSO₄·5H₂O, NaBH₄, MeOH
2) HCl, Et₂O

B2
1) Lindlar cat., H₂
2) HCl, Et₂O

**Hydrohydrazination, Hydroazidation**

- New direct access to hydrazines and azides from olefins
- First successful use of an “oxido-reductive” approach for the hydroamination of unactivated olefins
- Key to successful hydroazidation:
  - using sulfonyl azides as nitrogen sources
  - Discovery of the activating effect of t-BuOOH
- Detailed mechanistic investigation (with catalytic cycle) was presented
- High yields under operationally simple reaction conditions
**Co(II)-Salen-Catalyzed Cyclopropanation**

\[
\text{Ph} = \rightleftharpoons + \text{N} = \text{N}^+ \leftarrow \text{CO}_2\text{R} \xrightarrow{\text{Co(II)-salen complex, NMI, THF, N}_2, \text{rt}} \begin{array}{c}
\text{Ph} \\
+ \end{array} \xrightarrow{\text{CO}_2\text{R}} \begin{array}{c}
(1R,2S)\text{-isomer} \\
(1R,2R)\text{-isomer}
\end{array}
\]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Cat.</th>
<th>THF/Styrene</th>
<th>R</th>
<th>Yield (%)</th>
<th>cis:trans</th>
<th>% ee (cis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>9</td>
<td>100/1</td>
<td>t-Bu</td>
<td>88</td>
<td>92:8</td>
<td>96 (1R, 2S)</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>100/1</td>
<td>t-Bu</td>
<td>89</td>
<td>98:2</td>
<td>98 (1R, 2S)</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>10/6</td>
<td>Et</td>
<td>quant</td>
<td>99:1</td>
<td>96 (1R, 2S)</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>10/1</td>
<td>t-Bu</td>
<td>90</td>
<td>98:2</td>
<td>98 (1R, 2S)</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>100/1</td>
<td>t-Bu</td>
<td>18</td>
<td>97:3</td>
<td>99 (1S, 2R)</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>10/1</td>
<td>t-Bu</td>
<td>25</td>
<td>97:3</td>
<td>2 (1S, 2R)</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>10/6</td>
<td>t-Bu</td>
<td>91</td>
<td>27:73</td>
<td>95 (1R, 2S)</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>10/6</td>
<td>Et</td>
<td>quant</td>
<td>31:69</td>
<td>95 (1R, 2S)</td>
</tr>
</tbody>
</table>

\(^a\) The reaction was carried out in the absence of NMI.

\(^b\) The ee of the trans-isomer.

Tatsuya Uchida, Tsutomu Katsuki *Synthesis* **2006**, *10*, 1715-1723
Co(II)-Salen-Catalyzed Cyclopropanation

\[
\text{Ph} = + \text{N} = \text{N}^+ = \text{CO}_2\text{R} \quad \overset{\text{Co(II)-salen complex}}{\text{NMI}} \quad \text{THF}, \text{N}_2, \text{rt} \quad \rightarrow \quad \text{PhCO}_2\text{R} + \text{PhCO}_2\text{R}
\]

Tatsuya Uchida, Tsutomu Katsuki *Synthesis* **2006**, *10*, 1715-1723
Co(II)-Porphyrrin-Catalyzed Cyclopropanation

<table>
<thead>
<tr>
<th>Entry</th>
<th>Cyclopropane</th>
<th>Yield (%)</th>
<th>E:Z</th>
<th>ee (%)</th>
<th>[α]</th>
</tr>
</thead>
</table>
| 1     | \[
    \begin{array}{c}
    \text{MeO} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 96        | >99:1   | 98     | (-)  |
| 2     | \[
    \begin{array}{c}
    \text{O}_2\text{N} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 88        | >99:1   | 99     | (-)  |
| 3     | \[
    \begin{array}{c}
    \text{MeO} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 90        | >99:1   | 98     | (-)  |
| 4     | \[
    \begin{array}{c}
    \text{H}_2\text{N} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 90        | >99:1   | 88     | (-)  |
| 5     | \[
    \begin{array}{c}
    \text{Me} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 72        | >99:1   | 82     | (-)  |
| 6     | \[
    \begin{array}{c}
    \text{Bu} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 72        | >99:1   | 92     | (-)  |
| 7     | \[
    \begin{array}{c}
    \text{t-Bu} \\
    \text{CO}_2\text{R} \\
    \text{CN}
    \end{array}
    \] | 86        | >99:1   | 82     | (+)  |

R = +\text{N=NC}O_2\text{R} + \text{[Co(P1)]} → R−\text{CO}_2\text{R} + \text{CN}

Peter Zhang, Bas de Bruin et al J. Am. Chem. Soc. 2010, 132, 12796-12799
Co(II)-Porphyrin-Catalyzed Cyclopropanation ‘Carbene Radical’

Co(II)-Porphyrin-Catalyzed Cyclopropanation

Co(II)-Porphyrin-Catalyzed Cyclopropanation

Conclusion

- One-electron-reduced Fisher-type carbene play a key role
- Rare example of the involvement of a ligand radical in organometallic catalysis
- High reactivity and diastereo- and enantioselectivity with acceptor/acceptor-substituted diazo reagents
- First example of metal-catalyzed asymmetric intermolecular cyclopropanation with diazosulfones
- Obtained nonracemic cyclopropanes a myriad of synthetic and biological applications

Peter Zhang, Bas de Bruin et al J. Am. Chem. Soc. 2010, 132, 12796-12799
[6+2] cycloaddition

First enantioselective [6+2] cycloaddition phenylacetylene to CHT with 91 % yield, 74 % ee

M. Achard, A. Tenaglia, G. Buono Org. Lett. 2005, 7, 2353-2356
[6+2] cycloaddition

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ar</th>
<th>Yield/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ph</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>n-Bu</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>SiMe₃</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>CH₂C(Me)₂CH₂Ac</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>CH₂CH₂OAc</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>(CH₂)₃CN</td>
<td>88</td>
</tr>
<tr>
<td>7</td>
<td>H₂C(H₂C)₃N</td>
<td>94</td>
</tr>
<tr>
<td>8</td>
<td>CH₂SO₂Ph</td>
<td>71</td>
</tr>
<tr>
<td>9</td>
<td>CH₂OH</td>
<td>69</td>
</tr>
</tbody>
</table>

C-H – functionalization. Hydroarylation

Formation of Aryl-Aryl(Heteroaryl) Compounds

\[
\begin{align*}
\text{Ar}^1\text{Hal} + \text{Ar}^2\text{Hal} & \xrightarrow{20\% \text{CoBr}_2} \xrightarrow{20\% \text{PPh}_3} \xrightarrow{\text{Mn} (4 \text{ eq})} \xrightarrow{\text{DMF/pyridine} \ 6:1} \\
\text{Ar}^1\text{Hal} \xrightarrow{\text{Ar}^2\text{Hal} (\text{HetArHal})} & \xrightarrow{\text{Ar}^1\text{-Ar}^2 (\%)} \xrightarrow{\text{Ar}^2\text{-Ar}^2 (\%)}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ar\textsuperscript{1}Hal</th>
<th>Ar\textsuperscript{2}Hal (HetArHal)</th>
<th>Ar\textsuperscript{1}-Ar\textsuperscript{2} (%)</th>
<th>Ar\textsuperscript{2}-Ar\textsuperscript{2} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MeO-\text{C}6H\text{I}</td>
<td>Br-\text{C}6H\text{CN}</td>
<td>88</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>MeO-\text{C}6H\text{Br}</td>
<td>Cl-\text{C}6H\text{O-Me}</td>
<td>84</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Me-\text{C}6H\text{Br}</td>
<td>CN-\text{C}6H\text{N}</td>
<td>72</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>MeO-\text{C}6H\text{Cl}</td>
<td>Cl-\text{C}6H\text{F-F}</td>
<td>73</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>MeSO\text{C}6H\text{Cl}</td>
<td>Cl-\text{C}6H\text{O-Me}</td>
<td>60</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Br-\text{C}6H\text{O-}</td>
<td>Cl-\text{C}6H\text{Ph}</td>
<td>94</td>
<td>2</td>
</tr>
</tbody>
</table>

**Cobalt-Catalyzed Heck-Type Reaction**

\[
\text{Alk-X + } \overset{\text{cat. [CoCl}_2(\text{dpff})]}{\text{Me}_3\text{SiCH}_2\text{MgCl}} \overset{\text{ether}}{\rightarrow} \text{Alk} = \overset{\text{Ar}}{
\begin{array}{c|c|c|c|c}
\text{Entry} & \text{Alk-X} & \text{Time/h} & \text{Temp}/°C & \text{Yield/%} \\
\hline
1 & n-C_{6}H_{13}CH(Br)CH_{3} & 8 & 20 & 73 \\
2 & n-C_{12}H_{25}Br & 8 & 20 & 76 \\
3 & n-C_{12}H_{25}Br & 3 & 35 & 71 \\
4 & n-C_{12}H_{25}I & 3 & 35 & 57 \\
5 & n-C_{12}H_{25}Cl & 3 & 35 & 74 \\
6 & Ad-Br & 8 & 20 & 87 \\
7 & Ad-Cl & 3 & 35 & 90 \\
8 & c-C_{6}H_{11}Cl & 3 & 35 & 84 \\
9 & t-C_{4}H_{9}Br & 8 & 20 & 11 \\
10 & t-C_{4}H_{9}Br & 3 & 35 & 67 \\
11 & CH_{3}I & 3 & 35 & 55 \\
\end{array}
\]
Cobalt-Catalyzed Heck-Type Reaction

Cobalt-Catalyzed Heck-Type Reaction. Cyclization

Koichiro Oshima et al J. Am. Chem. Soc. 2006, 128, 8068-8077
Cobalt-Catalyzed Heck-Type Reaction

Conclusions

- CoCl$_2$(dppe) efficiently catalyzes a Heck-type reaction
- Mechanism is different from the palladium catalyzed one
- Reaction going via a radical pathway
- $\beta$-elimination is excluded
- Allowing to employ alkyl halides
- Procedure is simple and reaction tolerates a variety of functionalities
- Alkyl chlorides proved to be excellent alkyl sources in Heck-type reactions

Koichiro Oshima et al J. Am. Chem. Soc. 2006, 128, 8068-8077
Cocyclization 2-iodobenzoates with aldehyde

Cocyclization 2-iodobenzoates with aldehyde

\[
\text{Entry} \quad \text{Aldehyde} \quad \text{Yield (\%)} \quad \text{ee}
\]

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>89</td>
<td>84</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>80</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
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<td>85</td>
<td>91</td>
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<td>4</td>
<td></td>
<td>83</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>81</td>
<td>70</td>
</tr>
</tbody>
</table>

\[
\]

Conclusions

- First Co-catalyzed cocyclization 2-iodobenzoates with aldehyde
- Mild reaction conditions
- Inexpensive and efficient reaction
- High enantioselectivity
Conclusion

- Reactions are going under relatively mild conditions
- Powerful green low cost catalysts
- Low rates for β-hydride elimination pathway to compare with other metals
- High affinity to carbon-carbon π-bond, carbon-nitrogen π-bond
- Co-promoted various cycloadditions spanning from [2+1] to the [6+4]
- Small changes in the catalyst system or parameters such as solvent, ligand or concentrations lead to new unexpected results
Thank you for your attention!