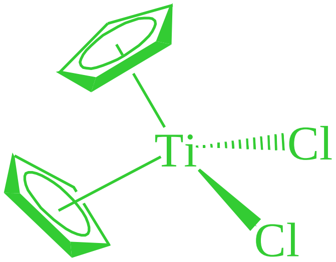
SOLUBLE Catalyst

1957



+ $AlCl(C_2H_5)_2$

The “Metallocene Revolution”

1980

Kaminsky e Sinn

SOLUBLE Catalysts

⇓

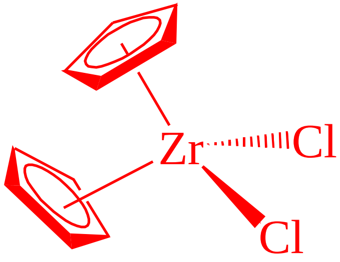
Catalyst **STRUCTURE**

⇓

Polymerization **MECHANISM**

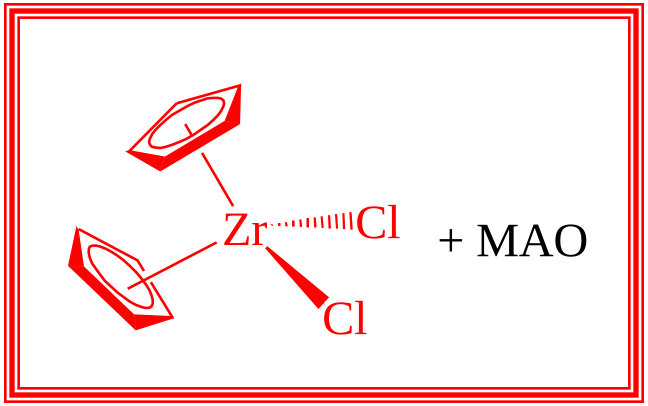
⇓

Polymer **STRUCTURE and PROPERTIES**



+ MAO

The "Metallocene Revolution"[1]

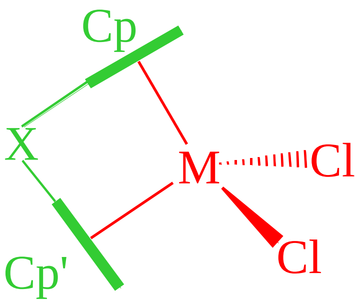


Features:

- homogeneous catalysts: 100 times more active than the conventional Ziegler-Natta (300 t PE/g Zr h);
- they catalyze the stereospecific polymerization of prochiral terminal alkenes;
- the synthesized polyolefins are featured by a narrow molecular weight distribution: Single Site Catalysts;
- branched poyolefins featured by branches of different length regularly distributed along the main chain are also obtained;
- these catalysts can be heterogenized.

[1] H. G. Halt et al., *Chem. Rev.* **2000**, *100*, 1205.

Metallocene Catalysts are very versatile

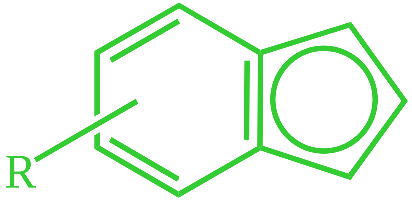


+ MAO

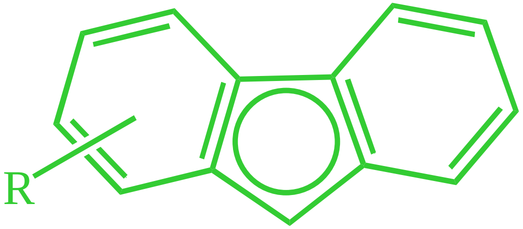
M = Ti, Zr, Hf

Cp = Cp’ o Cp ≠ Cp’

Cp e Cp’ =



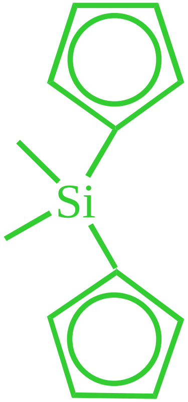
indenyl

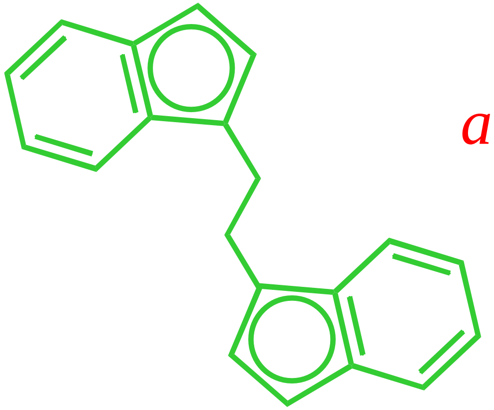


fluorenyl

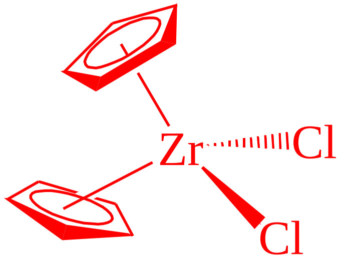
Cp-X-Cp’ =

$X = CH_2CH_2, R_2Si,$
R_2C





ansa-metallocenes



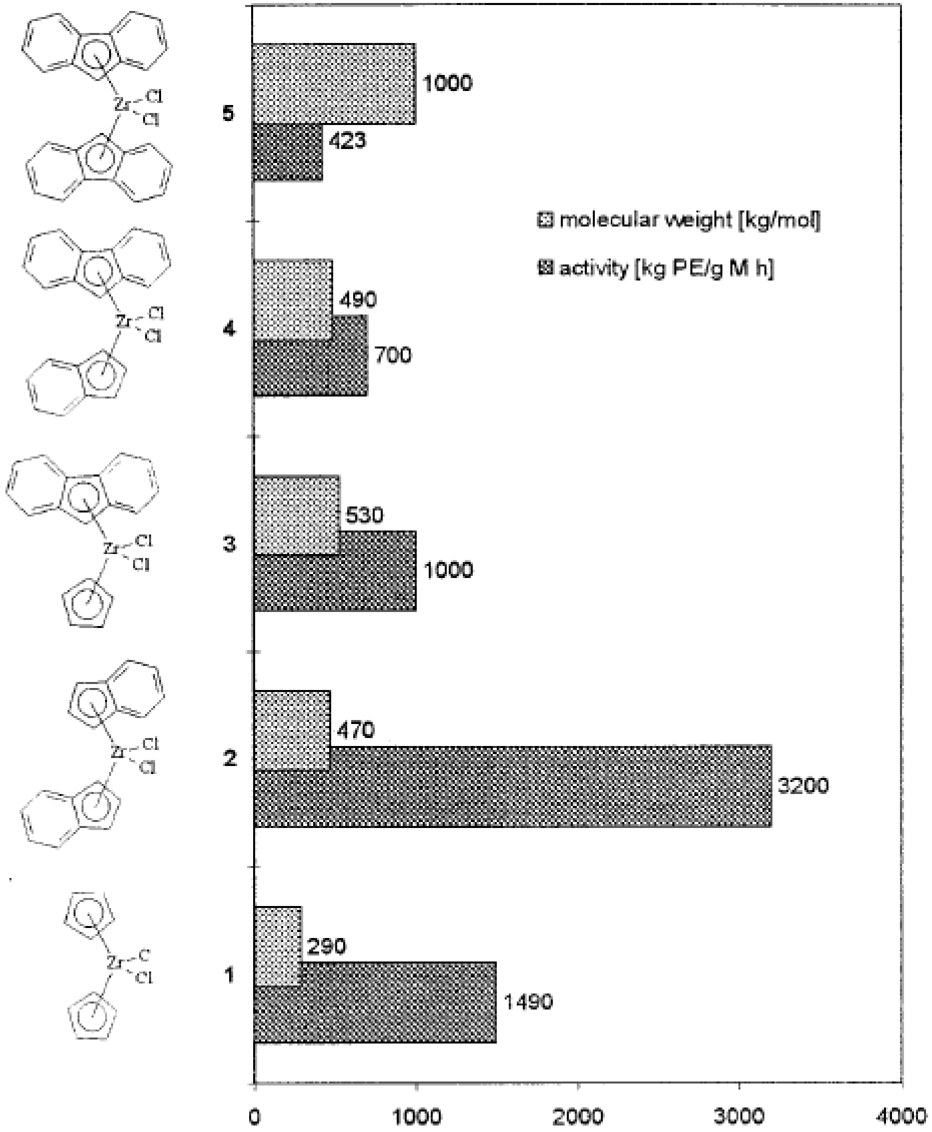
+ MAO

Reaction conditions: T = 90 °C, $P_{ethylene}$ = 8 bar,
[Al]/[Zr] = 10 000,
solvent = toluene

Productivity: $5 \cdot 10^6$ g PE/g Zr • h • bar
$M_n = 122\ 000$

T. Masuda, *Catalysis in Precision Polymerisation* **1997**, Ed. Wiley, pg. 18.

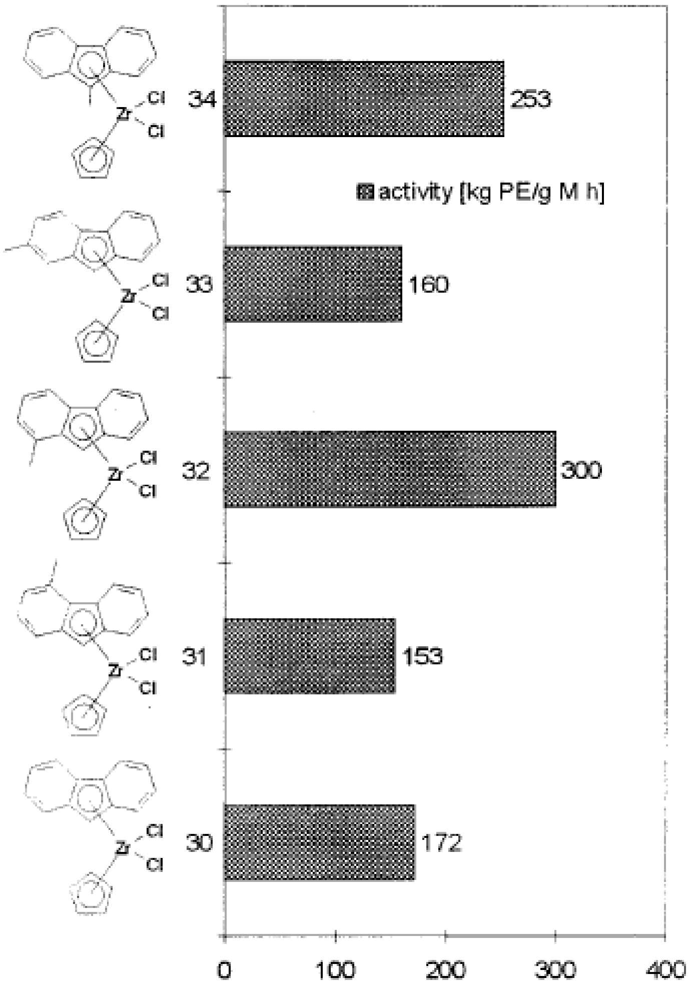
Ethylene polymerization: **Effect of the aromatic ring**



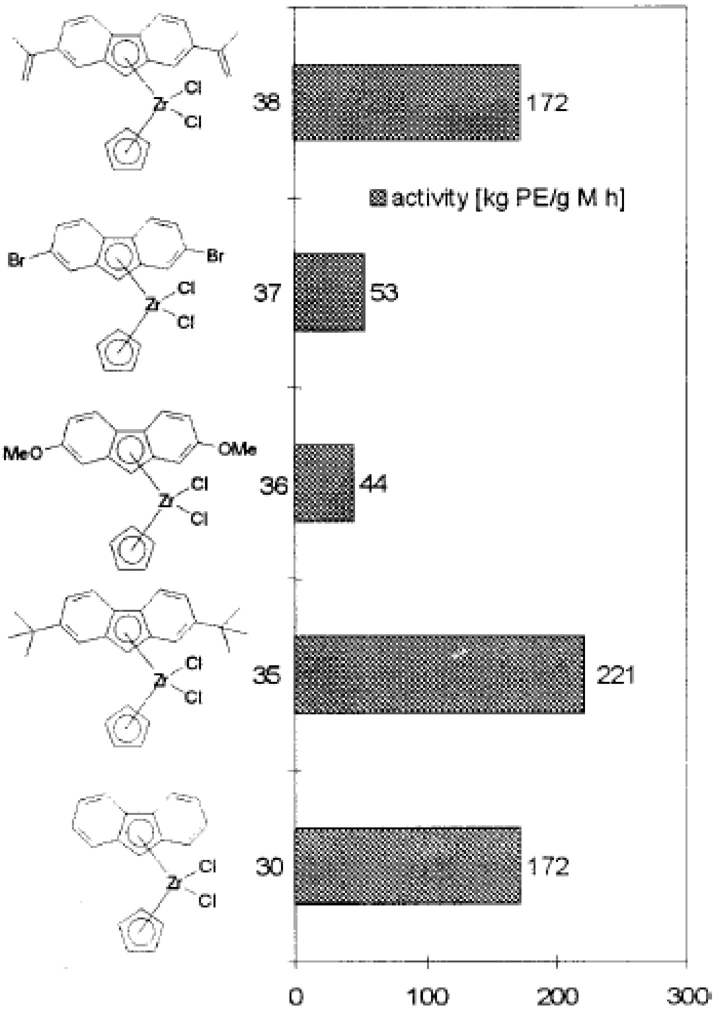
Reaction conditions: T = 60 °C; solvent: *n*-pentane; $P_{ethylene}$ = 10.0 bar; Cat. Prec. **1, 2, 4** [Al]/[Zr] = 1000; Cat. Prec. **3, 5** [Al]/[Zr] = 2500.

Ethylene polymerization: **Effect of**

substituent position



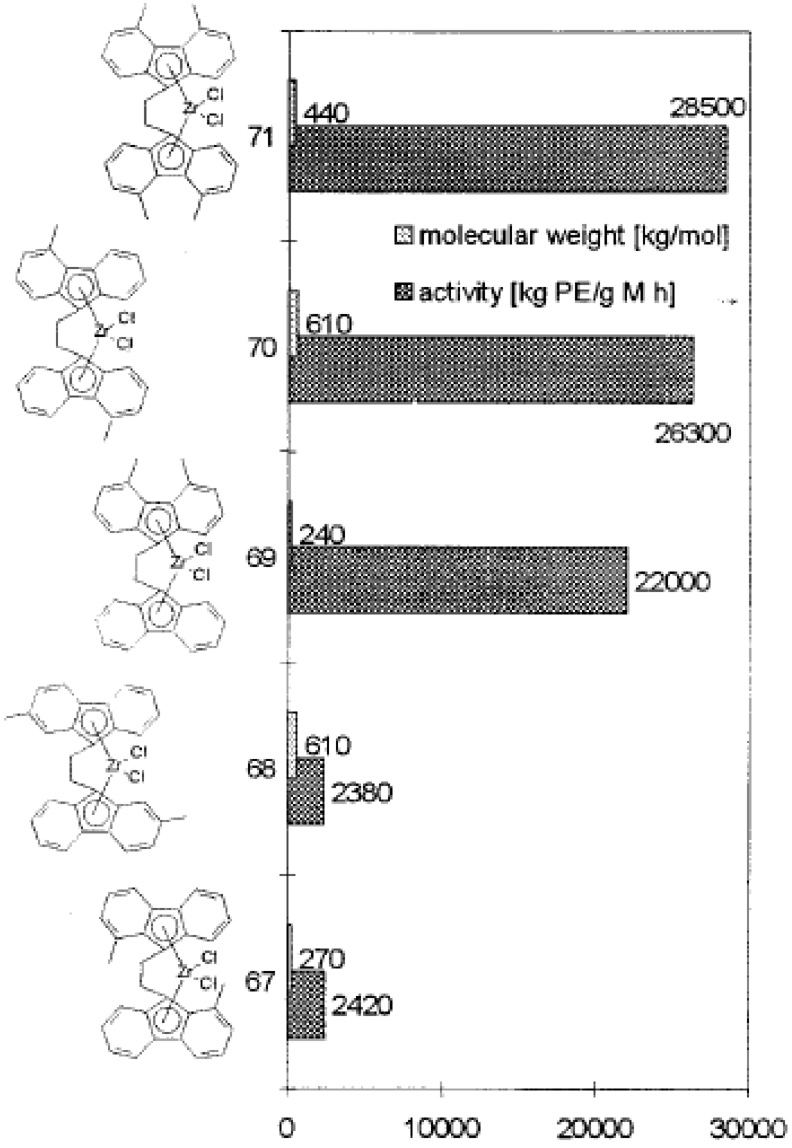
substituent nature



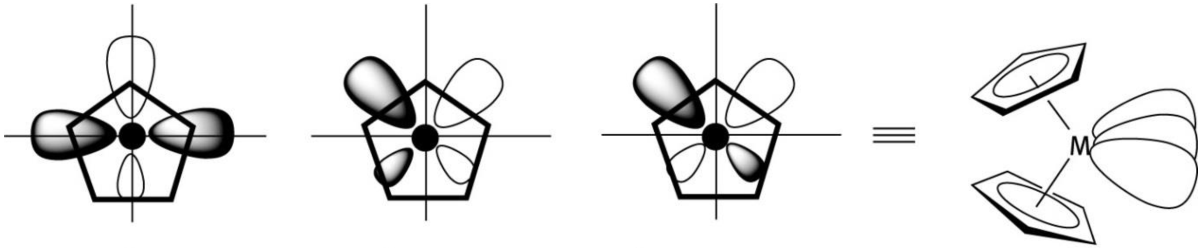
Reaction conditions: T = 10 °C; solvent: *n*-pentane; $P_{ethylene}$ = 10.0 bar; [Al]/[Zr] = 1000.

Ethylene polymerization: **Effect of substituent position in *ansa-metallocenes***

Reaction conditions:
T = 60°C;
solvent: *n*-pentane;
$P_{ethylene}$ = 10.0 bar;
[Al]/[Zr] = 20000.

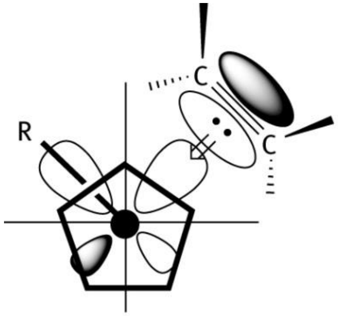


Frontier orbitals in $[Zr(Cp)_2]^{2+}$

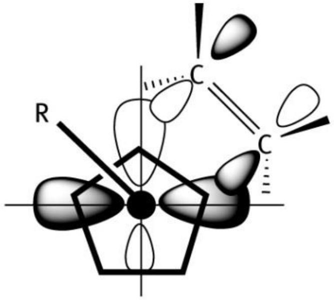


d_π $d_{\sigma}1$ $d_{\sigma}2$

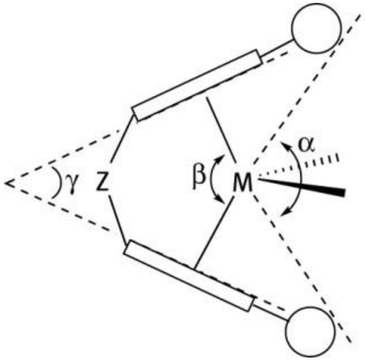
Frontier orbitals in $[Zr(Cp)_2R]^+$



d_σ acceptor orbital
for alkene binding

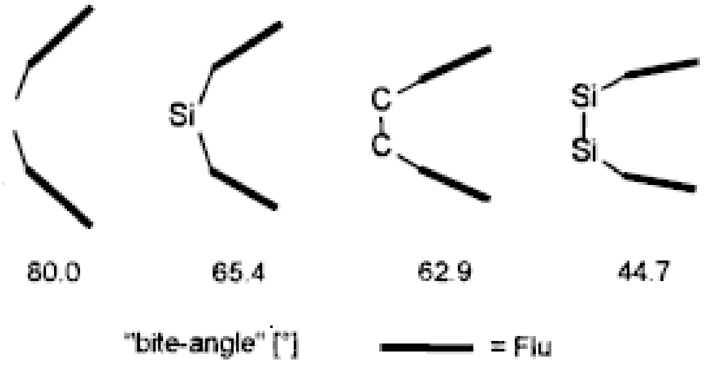


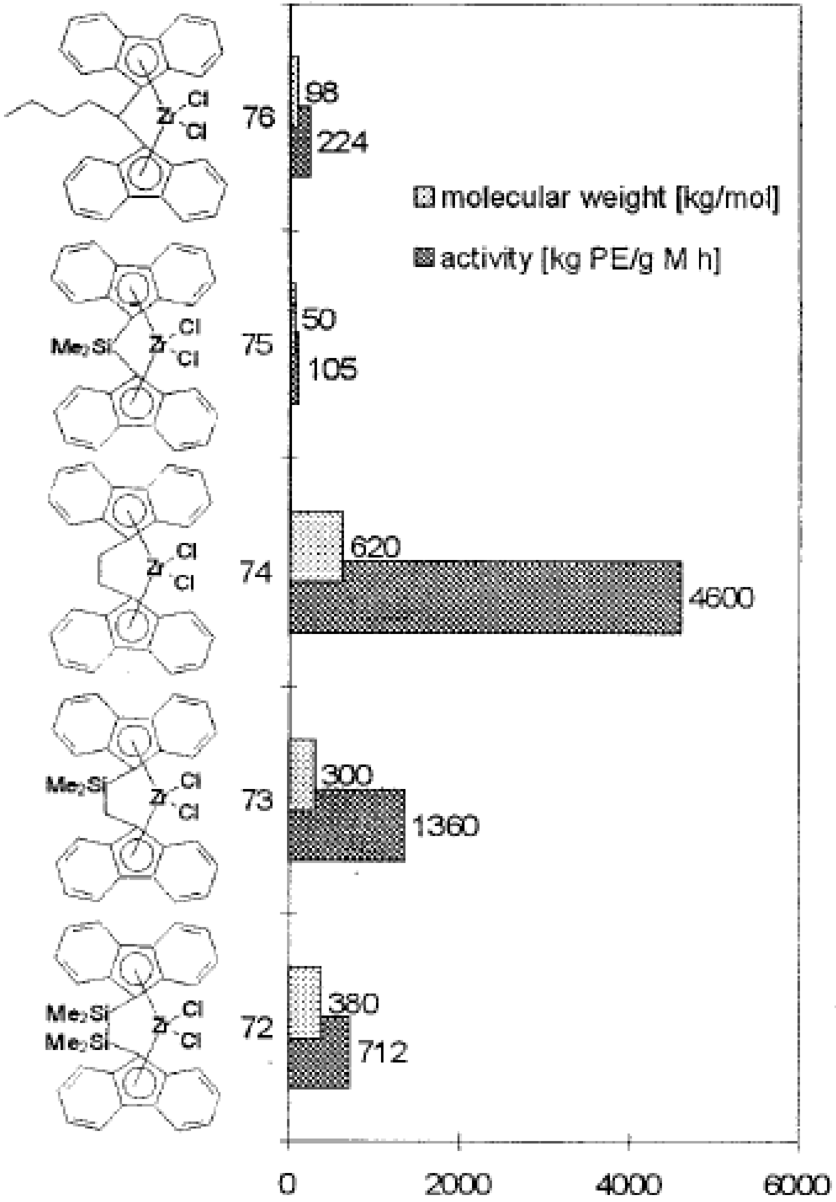
Orbital of d_π symmetry.
Absence of back-bonding for d^0 systems



coordination gap aperture, α,
and characteristic angles
in *ansa*-metallocenes

Ethylene polymerization: **Effect of ligand bite angle**

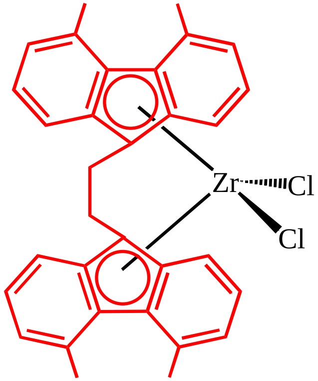




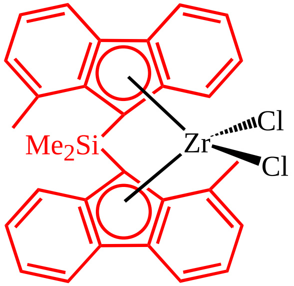
Reaction conditions: T = 60 °C; solvent: *n*-pentane; $P_{ethylene}$ = 10.0 bar; [Al]/[Zr] = 20000.

The “TOP FOUR” Catalysts[1]

productivity



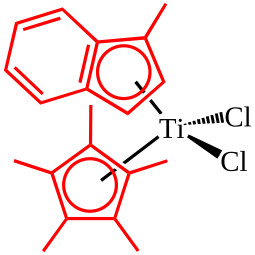
28 500 kg
PE/g Zr h



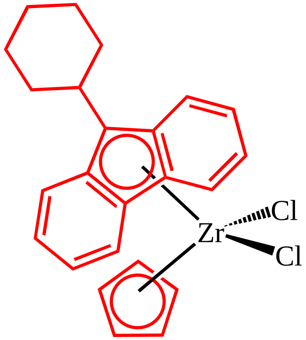
22 140 kg
PE/g Zr h

[Al]/[Zr] = 20 000

High molecular weight polyethylene



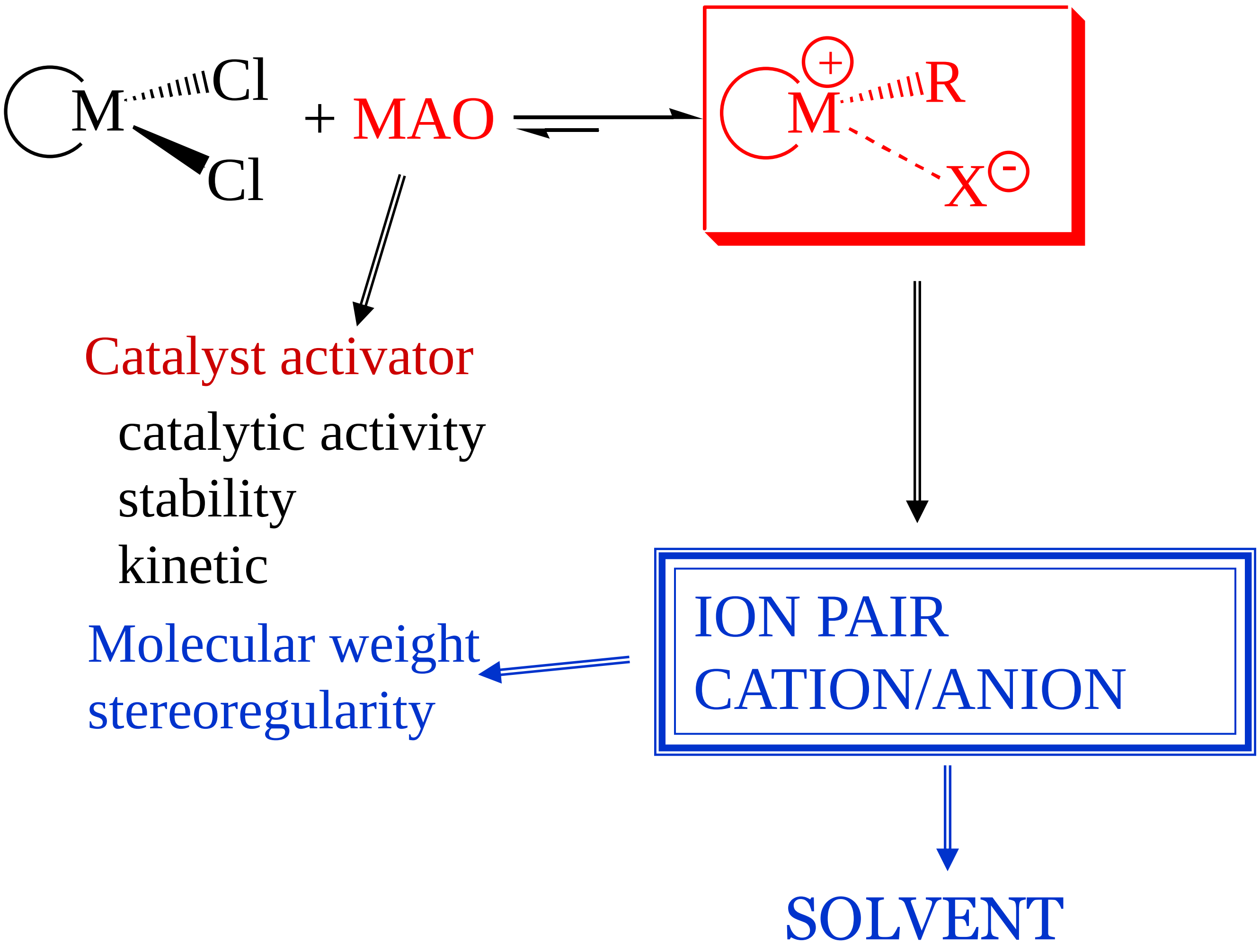
1 900 kg/mol



1 850 kg/mol

[1] H. G. Alt et al., *Chem. Rev.* **2000**, *100*, 1205.

Methylaluminoxane: MAO[1]



+ MAO

Catalyst activator

catalytic activity
stability
kinetic

Molecular weight
stereoregularity

ION PAIR
CATION/ANION

SOLVENT

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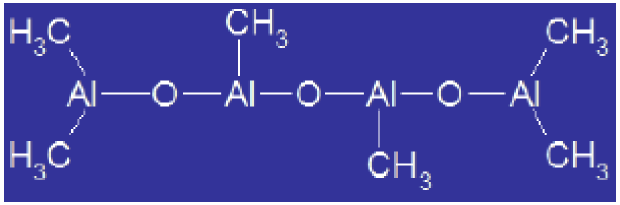
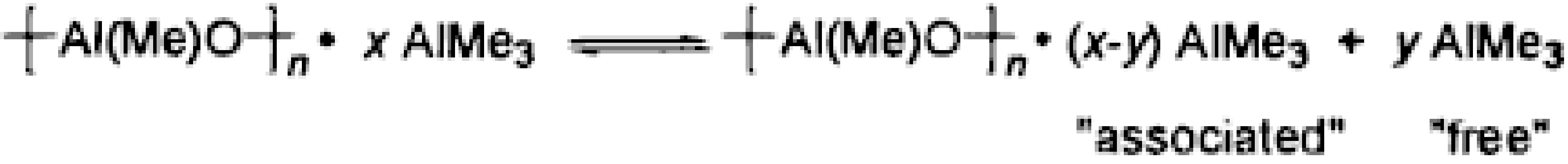
[1] T. J. Marks et al., *Chem. Rev.* **2000**, *100*, 1391.

MAO[1]: structural features

$[\text{—Al(Me)—O—}]_n$ n = 5 - 20

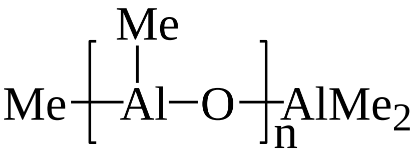


Multiple equilibria:



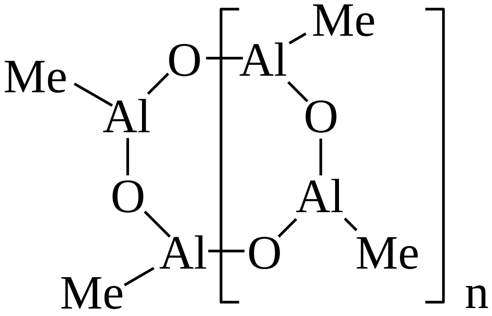
$$[\text{Al(Me)O}]_n \cdot x\,\text{AlMe}_3 \rightleftharpoons \underset{\text{"associated"}}{[\text{Al(Me)O}]_n \cdot (x\text{-}y)\,\text{AlMe}_3} + \underset{\text{"free"}}{y\,\text{AlMe}_3}$$

Main proposed structures :

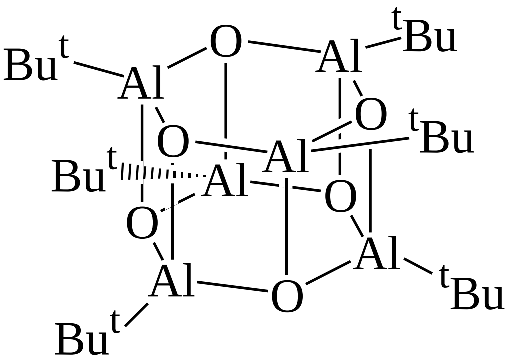


$$\text{Me}[\overset{\text{Me}}{\overset{|}{\text{Al}}}\text{—O}]_n\text{AlMe}_2$$

One-dimensional linear



Cyclic rings



Cage structure

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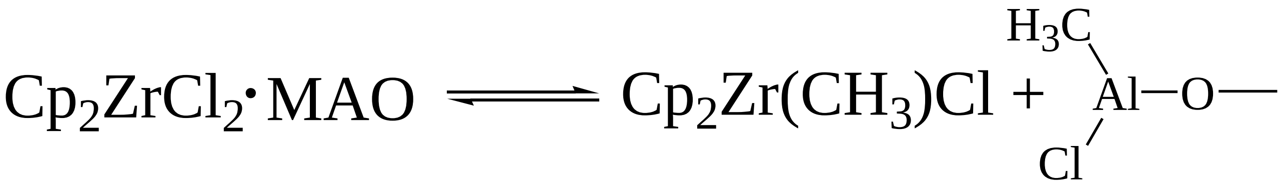
[1] T. J. Marks et al., *Chem. Rev.* **2000**, *100*, 1391.

MAO[1]: the activation process

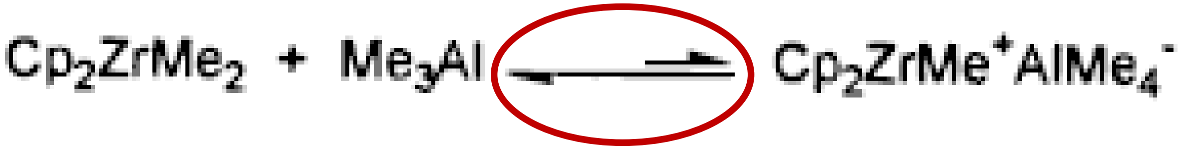
$$Cp_2ZrCl_2 + MAO \rightleftharpoons Cp_2ZrCl_2{\cdot}MAO$$ *Complexation*



$$Cp_2ZrCl_2{\cdot}MAO \rightleftharpoons Cp_2Zr(CH_3)Cl + (H_3C)(Cl)Al{-}O{-}$$ *Alkylation*

$$\begin{tikzcd} Cp_2Zr(CH_3)Cl + MAO \arrow[r, shift left] & Cp_2Zr(CH_3)Cl \cdot MAO \arrow[l, shift left] \arrow[d, shift left] \\ & \left[Cp_2Zr(CH_3)\right]^+ \left[Cl\text{-}MAO\right]^- \arrow[u, shift left] \end{tikzcd}$$ *Abstraction*

$$[Al]/[Zr] \geq 1000$$



$$Cp_2ZrMe_2 + Me_3Al \rightleftharpoons Cp_2ZrMe^+AlMe_4^-$$

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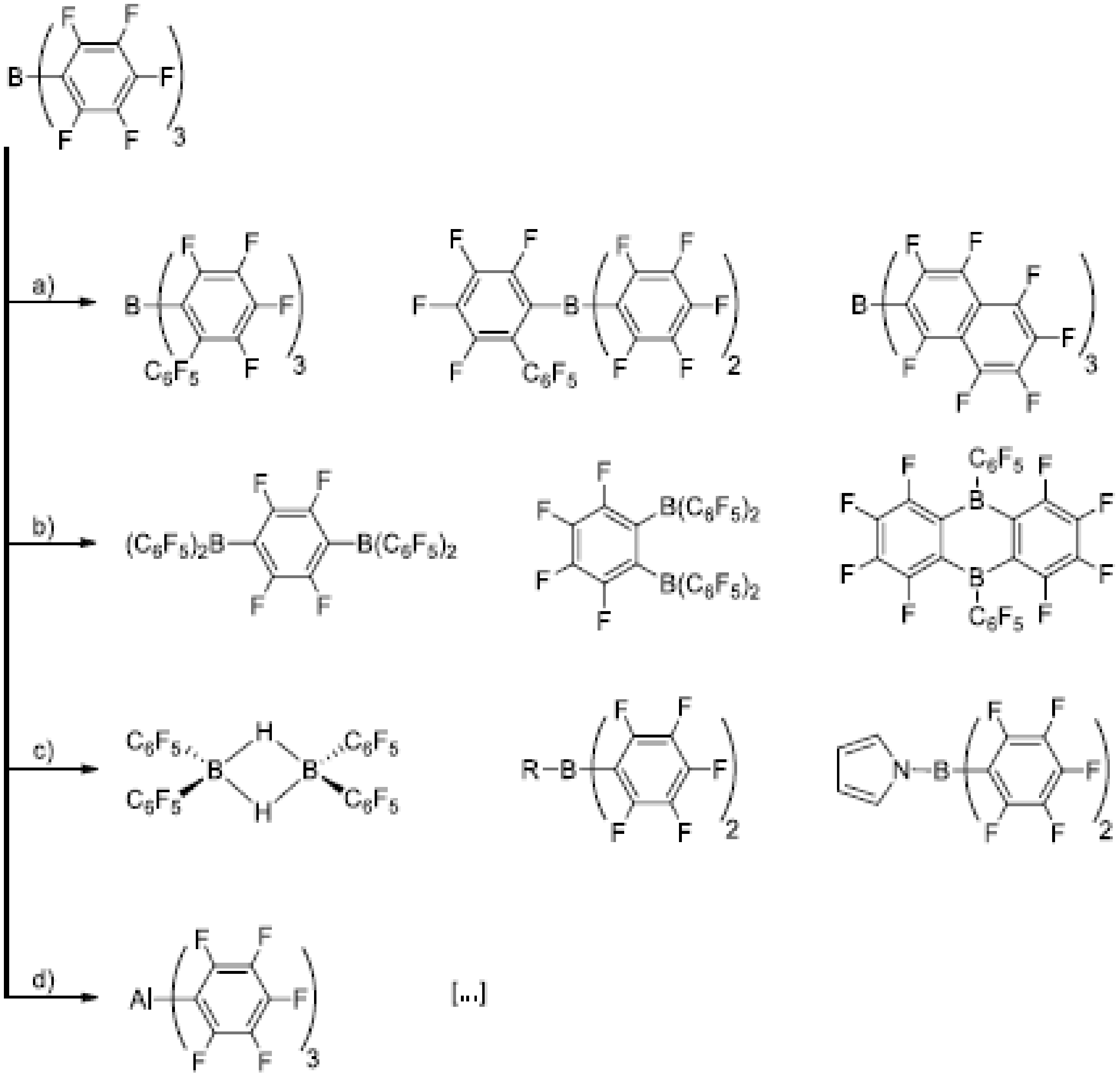
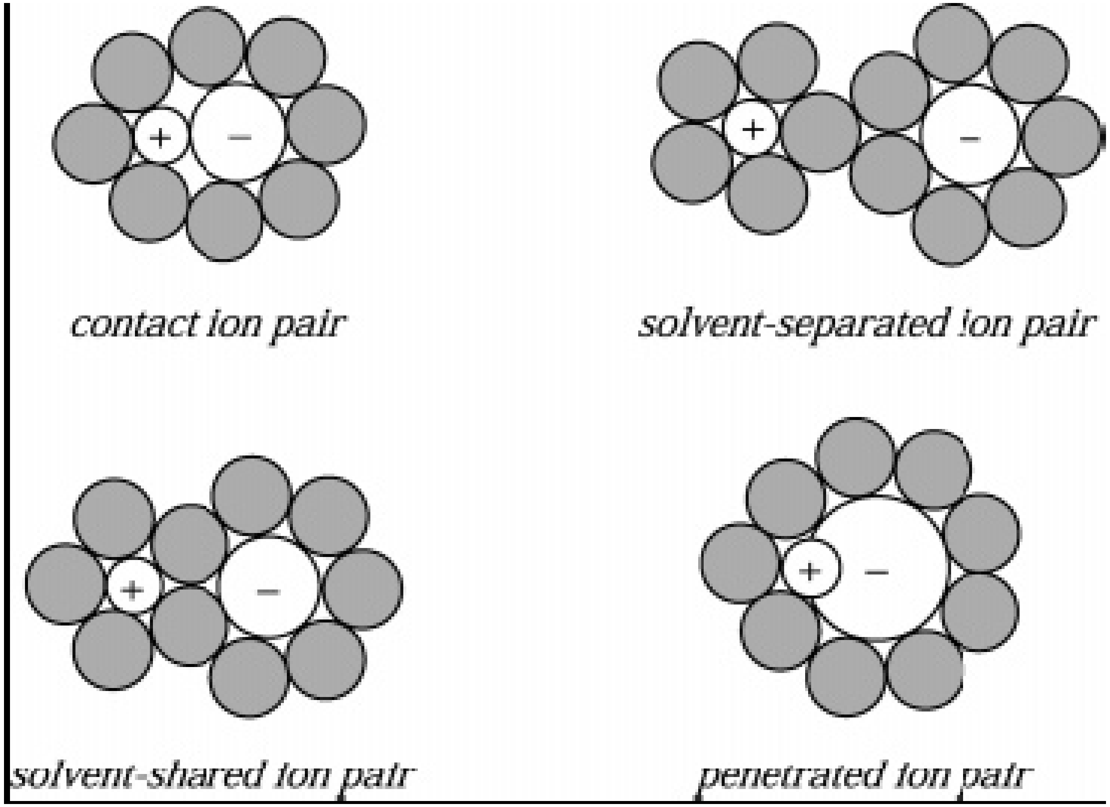
[1] T. J. Marks et al., *Chem. Rev.* **2000**, *100*, 1391.

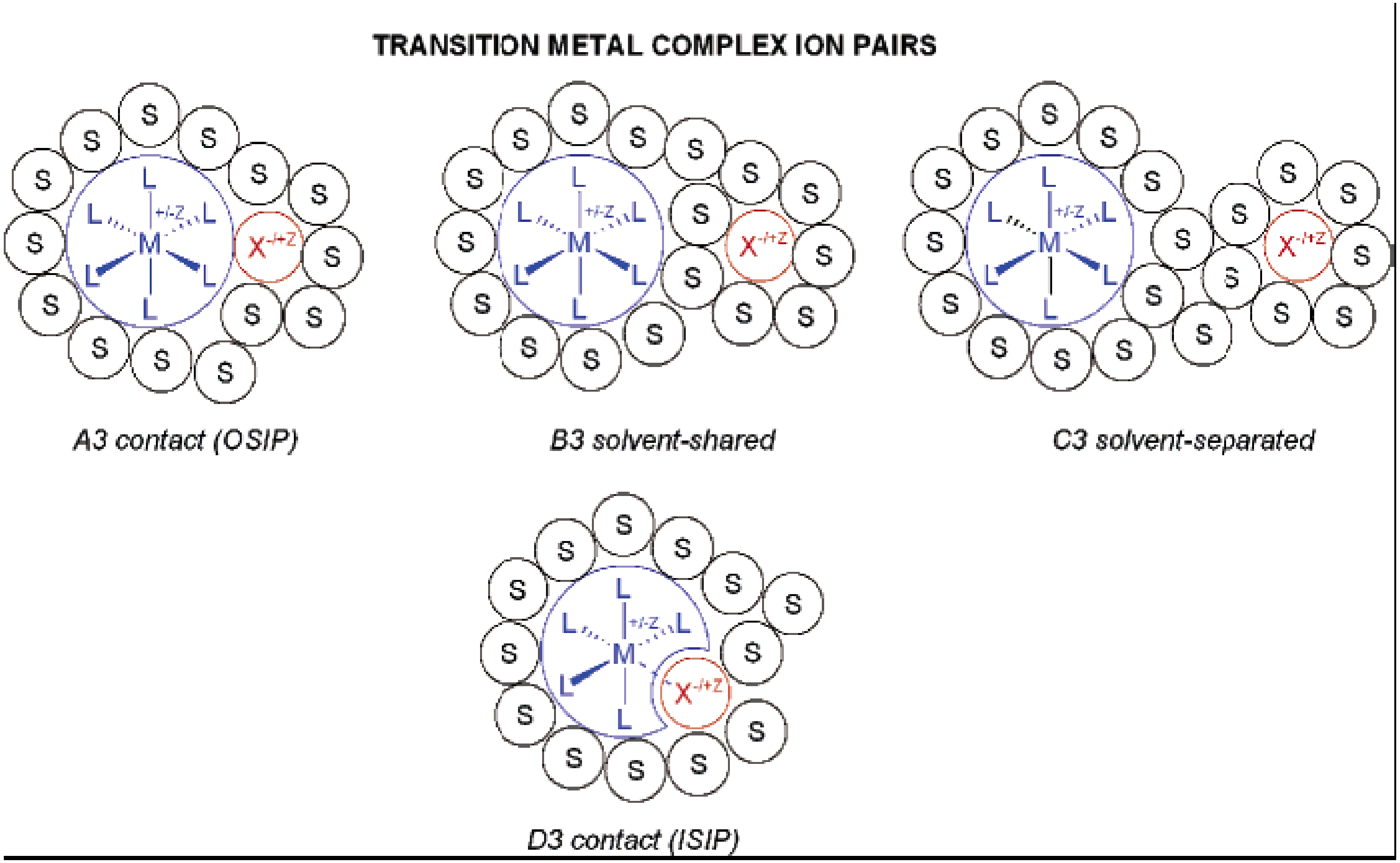
Lewis acids as activators: Perfluoroaryl boranes



THE ION PAIR[1]



[1] A. Macchioni *Chem. Rev.* **2006**, *105*, 2039.



TRANSITION METAL COMPLEX ION PAIRS

A3 contact (OSIP)

B3 solvent-shared

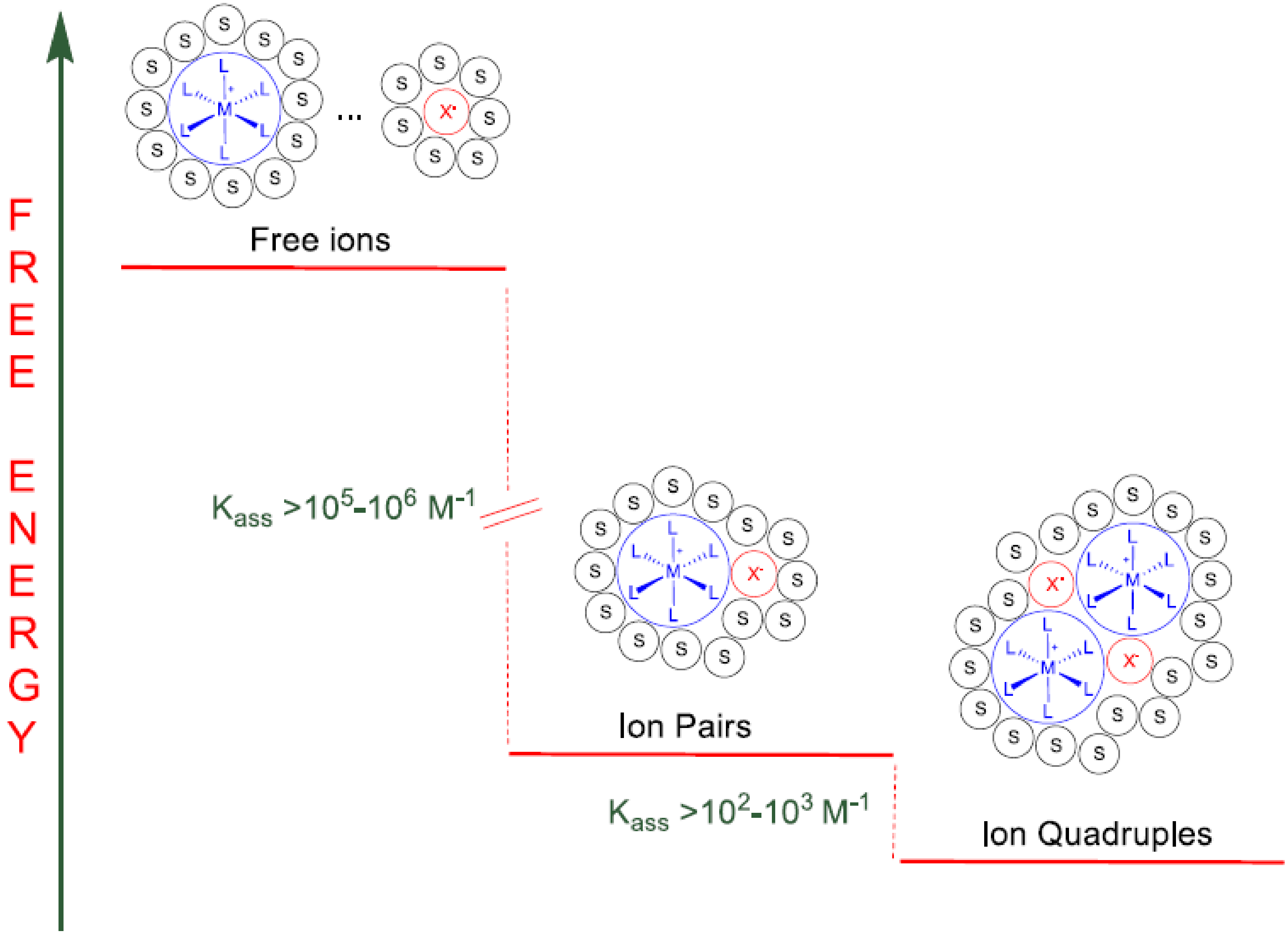
C3 solvent-separated

D3 contact (ISIP)

OSIP = OUTER-SPHERE ION PAIR

ISIP = INNER-SPHERE ION PAIR

Possible ion pairs in polymerization reactions



Free ions

$K_{ass} > 10^5$-10^6 M^{-1}

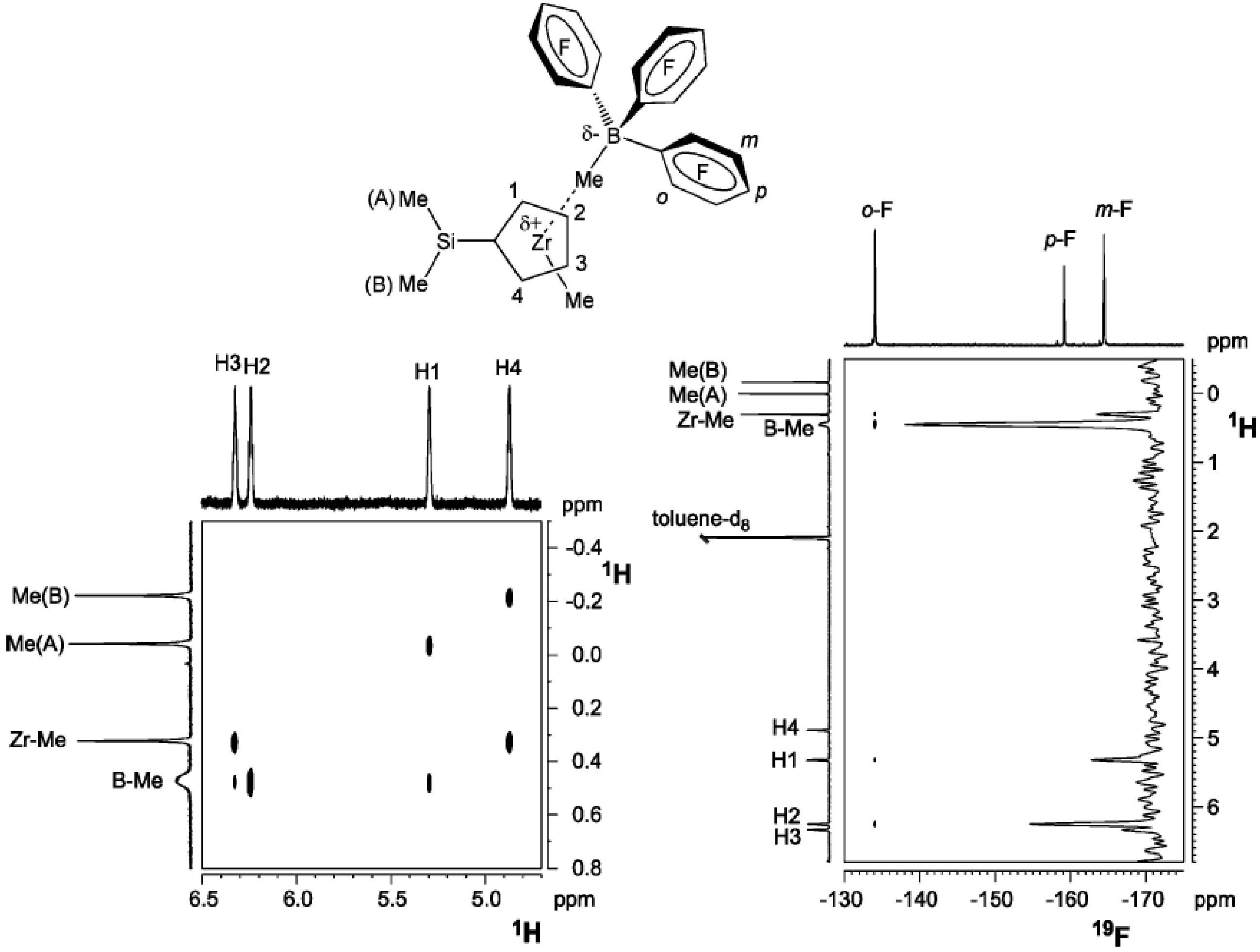
Ion Pairs

$K_{ass} > 10^2$-10^3 M^{-1}

Ion Quadruples

Experimental evidences for the ione pair formation

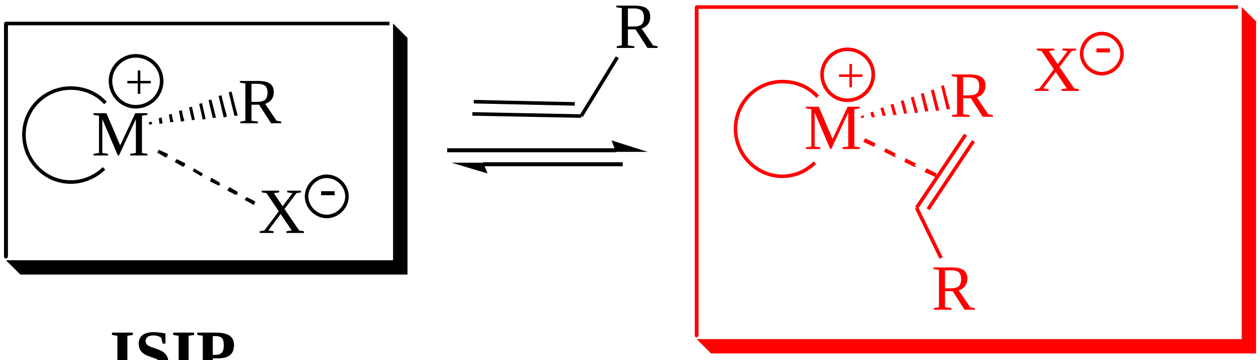
NMR Spectroscopy in solution



^{1}H-NOESY

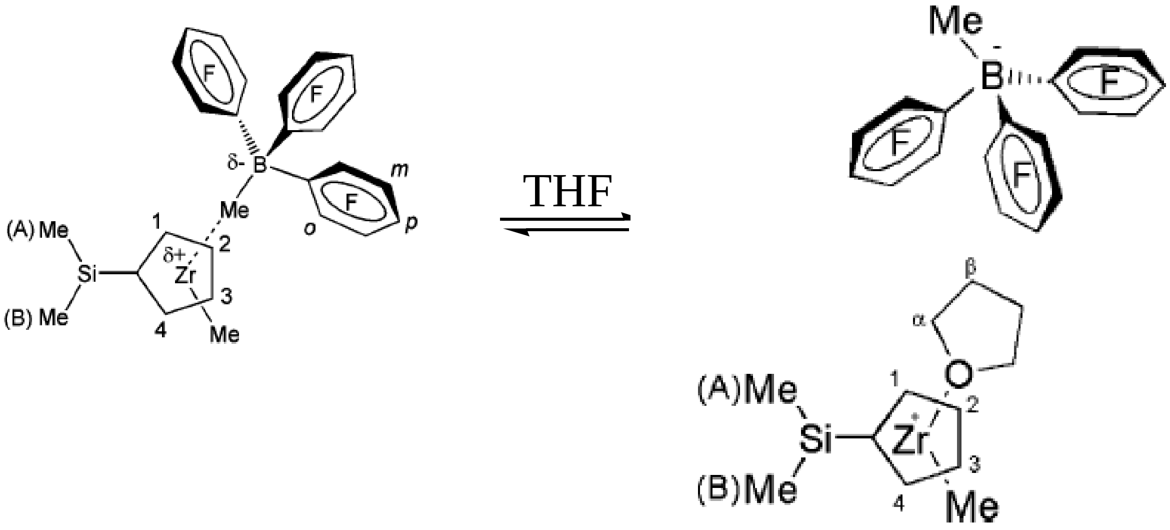
^{19}F ,^{1}H-HOESY

Accepted mechanism for the growth of polymer chain

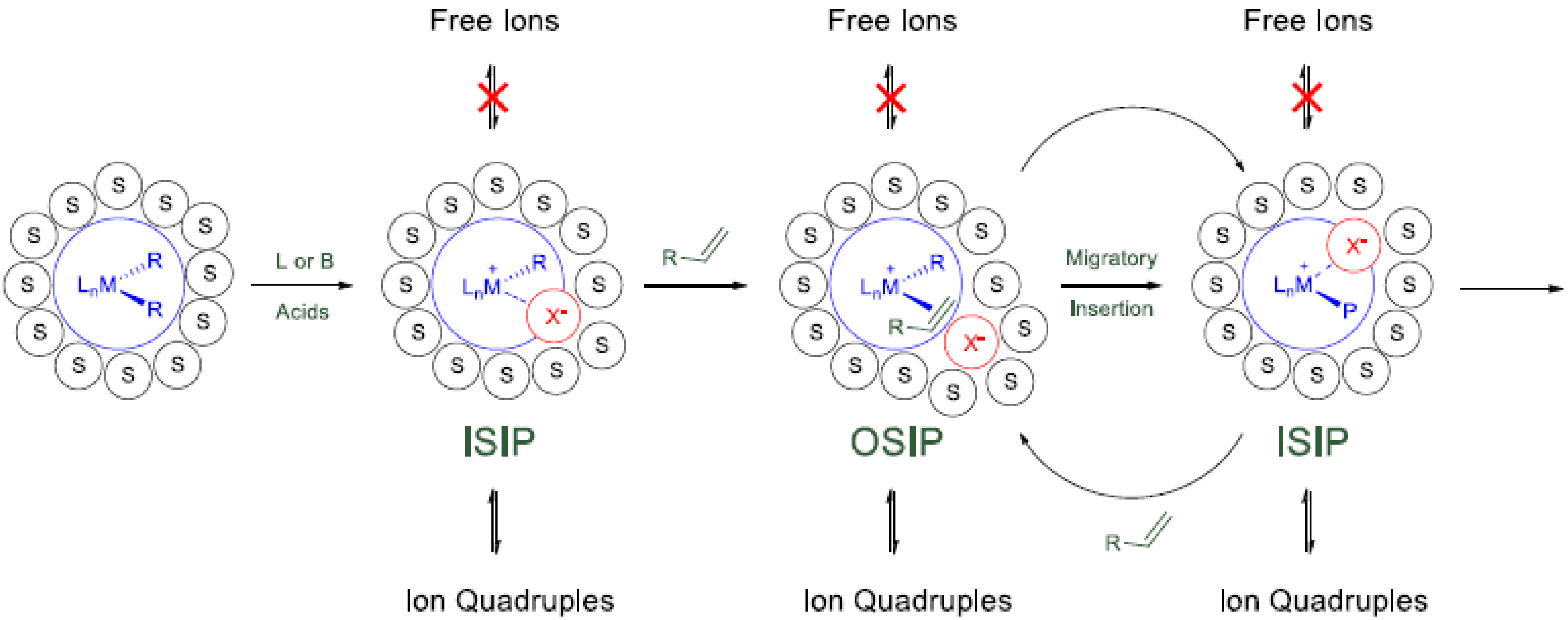


ISIP

OSIP

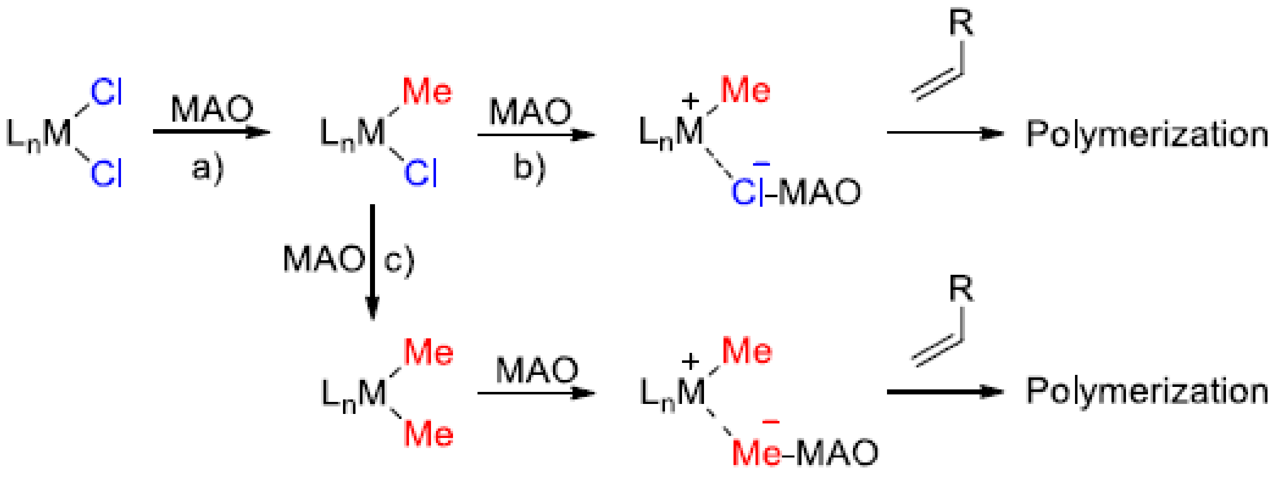


Overall mechanism for catalyst activation and growth of polymer chain

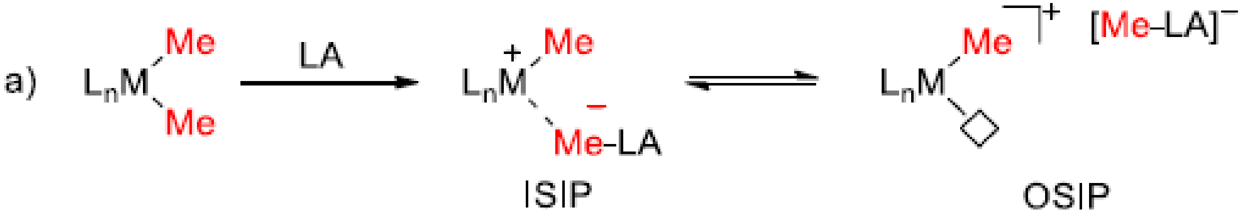


Activation process: a comparison

MAO as activation agent



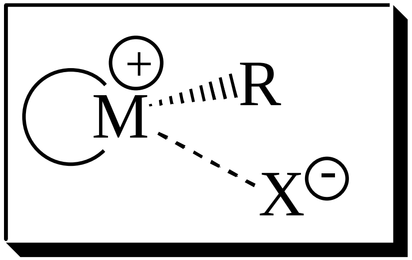
Boranes as activation agents



Ion pair effect in polymerization reactions

- the catalytic system is a two component system: the precatalyst that is a metallocene organometallic species and the catalyst activator that is an organometallic compound based on Al or on B;

- the two components react each other leading to the ion pair:



It is the catalyst ***resting state.***

ISIP

Effect of the anion in polymerization reactions

Catalytic activity increases on decreasing the coordination capability of the anion.

[(CGC)M(Me)][X]

When $X^- = MeB(C_6F_5)_3^-$

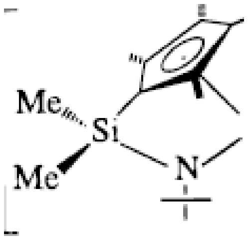
when M = Zr: inactive system

when M = Ti: slightly active system

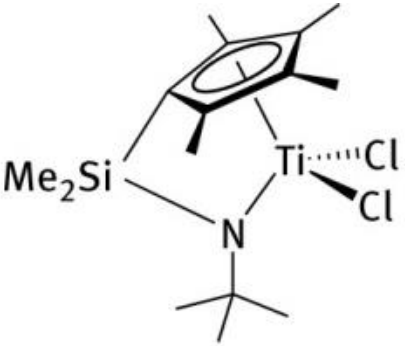
When X^- = MePBB$^-$

when M = Zr: active system: $v = 10^5$

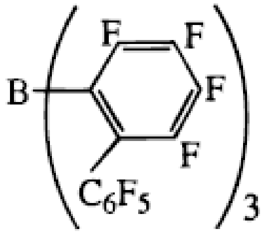
when M = Ti: the system is 70 times more active than the previous one



CGC



Cp-amido "constrained geometry" complex



PBB

Drawbacks of metallocene catalysts[1]

- They are easily poisoned by compounds containing heteroatoms;

- they are very expensive and are synthesized according to a multistep process;

- the use of MAO:
  i. in large excess with respect to the metal;
  ii. it has a relatively high cost, due to the high cost of $AlMe_3$;
  iii. high residual content of alumina in the final product;
  iv. intrinsic danger due to the use of extrimely pyrophoric $AlMe_3$.

[1] P. Chen et al., *Helv. Chim. Acta* **2002**, *85*, 4337.