

Catalyst composition and process for oligomerization of ethylene

The present invention relates to a catalyst composition and a process for the oligomerization of ethylene.

Linear alpha-olefins (LAOs) are very useful intermediates for the manufacture of detergents, synthetic lubricants, co-polymers, plasticizer alcohols and many other important products. There are several producers of such LAOs via oligomerization of ethylene, e.g. SHELL, BP, SABIC, AMOCO, CHEVRON PHILIPS etc.. An intrinsic problem of all of these metal-catalyzed ethylene oligomerization processes is the production of LAO mixtures following a mathematical distribution (Schulz-Flory or Poisson), which is difficult to separate and whose composition often does not match market demands. To solve this technical and economical unsatisfying situation, there is a deep interest to overcome the technical limitations and to transform the non-selective ethylene oligomerization reactions into more selective processes. Recently these activities are predominantly concentrated on the selective trimerization of ethylene to 1-hexene (review: D.H. Morgan et al. J. Organomet. Chem. 2004, 689, 3641; and refs. Cited therein) as well as the selective tetramerization of ethylene to 1-octene (recent review: D. Wass, Dalton Trans. 2007, 816).

Several patents for the trimerization of ethylene to 1-hexene and the tetramerization of ethylene to 1-octene are already known. In most of these cases different chromium precatalysts in combination with a broad array of different ligand systems and activating agents (like main group metal alkyl compounds) were utilized.

Prior art chromium based ethylene trimerization catalyst with chromium compounds, organoaluminum activators and different ligands are those listed e.g. in the following patent publications: US Patent 4,668,838; EP 0 668 105; US Patent 5,750,817; US Patent 6,031,145; US Patent 5,811,681; EP 537609; EP 1574492; US 2004783429; WO 2005039758; FR 2833191; US 2002035029; WO 2002004119; WO 2001083447 and EP 1110930. Here, various chelating and non-chelating donor ligands and a large number of Cr(III) precursor complexes were claimed. In WO 2003004158, Cr(II) complexes such as chromium(II)acetate were

claimed in conjunction with substituted cyclopentadienes as suitable ligand systems, in addition to the already described and utilized Cr(III) complexes. In WO 2003053891, also Cr(II) complexes such as, e.g., chromium(II)acetate are claimed. The claimed ligands are bis(2-diphenylphosphino-ethyl)amines and derivatives thereof.

Prior art ethylene tetramerization catalysts include a number of different transition metal compounds, organoaluminum activators or different ligands, that have been used in the same or slightly modified form for the trimerization process. Patents concerning the tetramerization are: US Patent No. 6,184,428; US Patent No. 3,676,523; DE Patent 14 43 927; US Patent No. 3,906,053; WO 2005/086251; WO 2006108803, WO 2006099053, WO 2007057455, WO 2007057458 and WO 2007088329. In most of these patents, the obtained mixture of olefins does not contain more than 25 weight-% 1-octene. In some of the most recent applications, different PNP- and similar chelating donor ligands were claimed in conjunction with Cr(III) complexes only (WO 2004/056478 and WO 2004/056479). These applications were the first to demonstrate that in ethylene oligomerization a high selectivity towards 1-octene (up to 70 mass-%) with significantly less simultaneous 1-hexene production can be achieved. It was pointed out that the formed nine-membered ring systems (chromacyclononane) are the reason for the selective tetramerization of ethylene to 1-octene with 70% mass selectivity.

The selective ethylene trimerization and tetramerization catalysts and processes known generally have to cope with some disadvantages. The catalysts show only low selectivities to the desired products 1-hexene and/or 1-octene due to by-products from side reaction channels. Further limited purities of the products are obtained, i.e. the selectivities within the specific C₆- or C₈-cut due to isomerization, branched olefin formation, etc.. Also wax formation, i.e. formation of heavy, long-chain, high carbon-number products is detected. This is also true for polymer formation (polyethylene, branched and/or cross-linked polyethylene) leading to considerable product yield loss and fouling of equipment. Further it has to be mentioned that prior art processes only show poor turnover rates and catalyst activity resulted in high cost per kg product. Prior art catalysts and ligands are usually to be prepared with high costs. Ligands are usually difficult to synthesize, resulting in poor availability and high catalyst cost. The catalyst performance is highly susceptible to trace impurities, and the catalyst components are often difficult to handle in technical environment. The prior art processes usually require

harsh reaction conditions, i.e. high temperatures and pressures, resulting in high invest, maintenance and energy costs. Finally, high costs are also to be expected for co-catalyst/activator.

It is therefore an object of the present invention to overcome the difficulties of the prior art and to provide a catalyst composition showing improved selectivities and purities in the oligomerization of ethylene without formation of wax or polymer, showing rather improved turnover rates with fair costs for preparing catalyst and ligand.

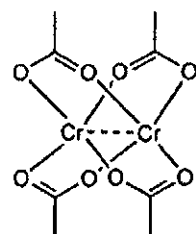
Additionally, a process for the oligomerization of ethylene shall be provided.

The first object is achieved by a catalyst composition comprising: (a) a binuclear chromium(II) complex; (b) a ligand of the general structure (A) $R_1R_2P-N(R_3)-P(R_4)-N(R_5)-H$ or (B) $R_1R_2P-N(R_3)-P(R_4)-N(R_5)-PR_6R_7$, wherein R_1 , R_2 , R_3 , R_4 , R_5 , R_6 and R_7 are independently selected from halogen, amino, trimethylsilyl, C_1 - C_{10} -alkyl, aryl and substituted aryl, wherein the PNP- or PNP- unit is optionally part of a ring system; and (c) an activator or co-catalyst.

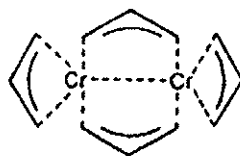
As is to be understood, any cyclic derivatives of (A) and (B) can be utilized as ligand, wherein at least one of the P or N atoms of the PNP- unit (structure (A)) or PNP- unit (structure (B)) is a ring member, the ring being formed from one or more constituent compounds of structures (A) or (B) by substitution, i. e. by formally eliminating per constituent compound either two whole groups R_1 - R_7 (as defined) or H, one atom from each of two groups R_1 - R_7 (as defined) or a whole group R_1 - R_7 (as defined) or H and an atom from another group R_1 - R_7 (as defined), and joining the formally so-created valence-unsaturated sites by one covalent bond per constituent compound to provide the same valence as initially present at a given site.

Preferably, the chromium complex has a Cr-Cr-bond or two chromium centres are connected via a bridging ligand.

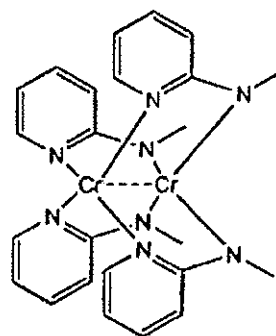
Most preferably, the binuclear chromium complex is selected from:



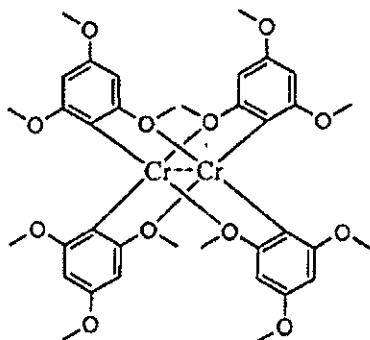
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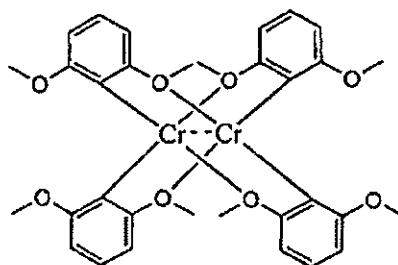
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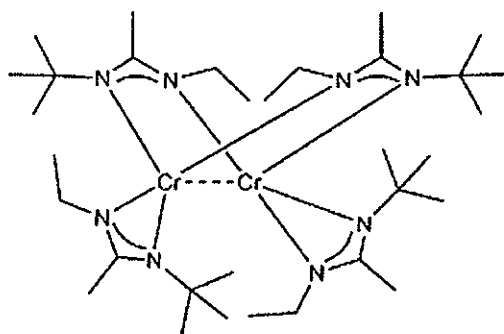
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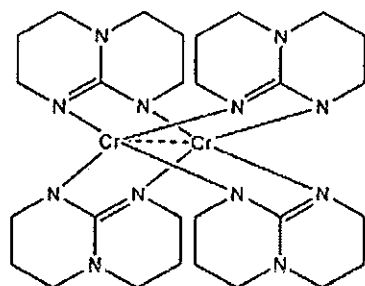
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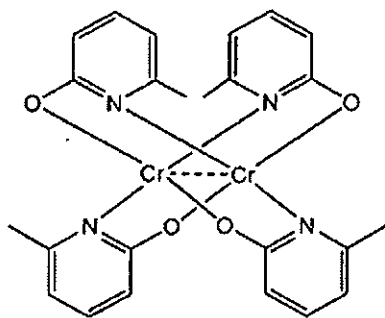
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In one embodiment, R_1 , R_2 , R_3 , R_4 , R_5 , R_6 and R_7 are selected from chloro, amino, trimethylsilyl, methyl, ethyl, isopropyl, tert-butyl, phenyl, benzyl, tolyl and xylyl.

In another embodiment, the activator or co-catalyst is selected from trimethyl aluminium, triethyl aluminium, triisopropylaluminum, triisobutyl aluminium, ethylaluminum sesquichloride, diethylaluminum chloride, ethyl aluminium dichloride, methylaluminoxane (MAO) or mixtures thereof.

The ligand may be selected from $(\text{Ph})_2\text{P-N}(\text{i-Pr})\text{-P}(\text{CH}_3)\text{-N}(\text{i-Pr})\text{-H}$, $(\text{Ph})_2\text{P-N}(\text{i-Pr})\text{-P}(\text{Ph})\text{-N}(\text{i-Pr})\text{-H}$, $(\text{Ph})_2\text{P-N}(\text{i-Pr})\text{-P}(\text{Ph})\text{-N}(\text{Ph})\text{-H}$, $(\text{Ph})_2\text{P-N}(\text{i-Pr})\text{-P}(\text{Ph})\text{-N}(\text{tert-butyl})\text{-H}$ and $(\text{Ph})_2\text{P-N}(\text{i-Pr})\text{-P}(\text{Ph})\text{-N}(\text{CH}(\text{CH}_3)(\text{Ph}))\text{-H}$.

Preferably, the catalyst composition comprises a solvent, which may be selected from aromatic hydrocarbons, straight-chain and cyclic aliphatic hydrocarbons, straight-chain olefins and ethers, preferably toluene, benzene, ethyl benzene, cumene, xylenes, mesitylene, hexane, octane, cyclohexane, methylcyclohexane, hexene, heptene, octene, diethylether or tetrahydrofuran or mixtures thereof, most preferably toluene.

A second object of the invention is achieved by a process for oligomerization of ethylene, comprising subjecting a catalyst composition according to the invention to a gas phase of ethylene in a reactor and conducting an oligomerization.

Preferably, the oligomerization is carried at a pressure of 1 to 200 bar, preferably 10 to 50 bar.

Also preferred, the oligomerization is carried at a temperature of from 10 to 200°C, preferably 20 to 100°C.

In one embodiment, the process is carried out continuously, semi-continuously or discontinuously.

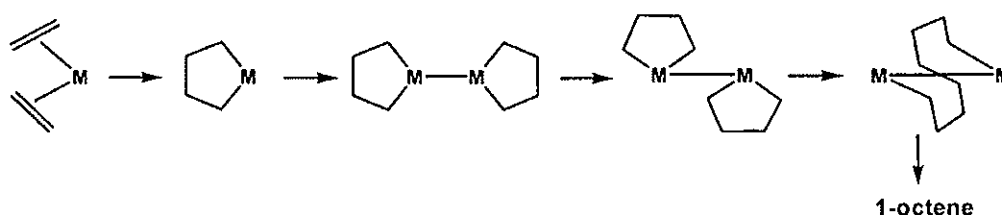
The mean residence time may be from 10 minutes to 20 hours, preferably 1 to 4 hours.

Most preferred, the process is a trimerization or tetramerization.

Surprisingly it was found that a process for oligomerization of ethylene utilizing the inventive catalyst composition avoids the broad spectrum of LAO products and allows for the selective production of the economically most desired products, namely 1-hexene and 1-octene. Unprecedented high selectivity, purity and sufficiently high active/turnover frequency are achieved.

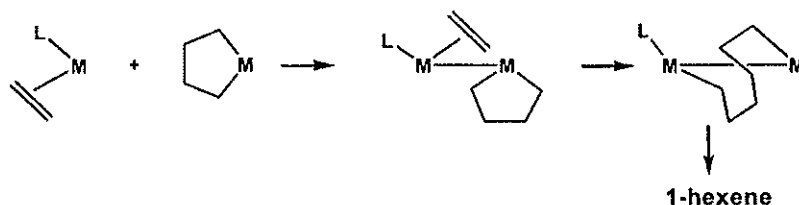
The current invention is based on the fact that the selective tetramerization of ethylene to 1-octene and the trimerization of ethylene to 1-hexene can proceed more efficiently by using a binuclear transition metal complex, rather than a mononuclear transition metal complex, whose mechanism involves mononuclear metallocyclononanes and metallacycloheptanes, respectively.

Without wishing to be bound to any theory, it is assumed that for the binuclear chromium complexes utilized in a tetramerization reaction a mechanism is suggested wherein the reaction proceeds via metallocyclopentanes which the C₄-chain dimerizes to a saturated C₈-chain between the metal centers as illustrated in the following scheme:



The above mechanism is characterized by the novel principle of a dinuclear reductive elimination from chromium(II) via chromium(I) to chromium(0) leading to 1-octene.

The catalyst composition according to the present invention can be tuned by suitable ligands to the novel principle of dinuclear reductive elimination from chromium(0) via chromium(I) to chromium(0) (case: neutral ligands) or from chromium(I)/(II) via chromium(II)/(I) to chromium(I)/(0) (case: anionic ligands) leading selectively to 1-hexene:



Additionally, it was surprisingly found that the modification of a tridentate ligand, such as $(phenyl)_2P-N(isopropyl)-P(phenyl)_2$ by an additional $NH(isopropyl)$ unit resulted in the tetradentate ligand $((phenyl)_2PN(isopropyl)P(phenyl)NH(isopropyl))$. Utilizing the former ligand in the catalyst composition resulted in a high selectivity towards the tetramerization of ethylene, whereas the latter ligand resulted in a high selectivity for the trimerization or tetramerization of ethylene depending on the substituents, as will be shown below in the examples section.

In other words, the inventive process results in the production of 1-octene and 1-hexene with high turnover rate and selectivity. An easy switchover from 1-octene to 1-hexene production by using specific ligands can be easily obtained. Further, a high reproducibility is obtained, e.g. the catalyst system is stable against interference from impurities and fluctuations in process conditions. Formation of wax and polymers is well suppressed. Additionally, in the inventive process slight reaction conditions may be employed, consequently resulting in low investment costs for technical-scale plant and low energy and operation costs.

Additional advantages and features of the present invention will become apparent from the following detailed description on the basis of examples.

A ligand to be used in the inventive catalyst composition may be prepared as follows:

Preparation of $\text{Ph}_2\text{PN}(\text{i-Pr})\text{PMeNH}(\text{i-Pr})$: 2,21 g of Ph_2PCl (10 mmol) was slowly added to a mixture of 1,62 g $\text{MeP}(\text{NH}(\text{i-Pr}))_2$ (10mmol) (Eur. J. Inorg. Chem. 1999, 12, 2355-68) and 5ml triethylamine in 15 ml toluene at 0°C. The solution was stirred for additional 2h at r.t. and then filtered to remove the amine-hydrochloride. After evaporation of the volatile compounds in vacuo a sticky oil remained. Yield: 80%

^{31}P -NMR (C_6D_6); 33.7, 57.6 (broad)

Trimerization by binuclear complexes

Example 1:

Ethylene trimerization using $\{[(\text{i-Pr})_2\text{N}]\text{Cr}[\mu-(\text{i-Pr})_2\text{N}]\}_2$, $((\text{phenyl})_2\text{PN}(\text{isopropyl})\text{P}(\text{phenyl})\text{NH}(\text{isopropyl}))$ and triethylaluminum

A 300 ml pressure reactor, equipped with dip tube, thermowell, gas entrainment stirrer, cooling coil, control units for temperature, pressure and stirrer speed (all hooked up to a data acquisition system) was inertized with dry argon and filled with 100 ml anhydrous toluene. Then 81.7 mg (0.2 mmol) of $((\text{phenyl})_2\text{PN}(\text{isopropyl})\text{P}(\text{phenyl})\text{NH}(\text{isopropyl}))$ in 10 ml toluene was combined with 65.6 mg $\{[(\text{i-Pr})_2\text{N}]\text{Cr}[\mu-(\text{i-Pr})_2\text{N}]\}_2$ (0.13 mmol) under an argon blanket. This catalyst solution was transferred to the reactor under constant argon flow, along with 3.6 ml of a 1.9 mol/l solution of triethylaluminium in toluene.

The reactor was sealed, pressurized with 30 bar dry ethylene and heated to 50°C. While stirring at 1200 rpm, the ethylene consumption was monitored by the data acquisition system and an electronic balance by constantly weighing the ethylene pressure cylinder. After 120 min residence time, the reaction in the liquid phase was quenched by transferring the liquid inventory by means of the ethylene pressure to a glass vessel filled with approx. 100 ml of water. The entire gas phase from the reactor's head space was quantified by a calibrated gas meter and was then collected quantitatively in a purged and evacuated gas bag.

After separation of the liquid organic phase, the total mass was determined by weighing. Subsequently, the composition of the organic phase was analyzed separately by GC/FID. Based on the measured data, the mass balance was closed and the overall yields and selectivities were determined. The product distribution of this example is summarized in Table 1.

Comparative Example 2:

Ethylene trimerization using $\text{CrCl}_3(\text{tetrahydrofuran})_3$, $((\text{phenyl})_2\text{PN}(\text{isopropyl})\text{P}(\text{phenyl})\text{NH}(\text{isopropyl}))$ and triethylaluminum

In analogy to Example 1 a 300 ml pressure reactor was filled with 100 ml anhydrous toluene. A solution of 81.7 mg (0.2 mmol) of $((\text{phenyl})_2\text{PN}(\text{isopropyl})\text{P}(\text{phenyl})\text{NH}(\text{isopropyl}))$ in 10 ml toluene was combined with 50.0 mg (0.13 mmol) $\text{CrCl}_3(\text{tetrahydrofuran})_3$ under a argon blanket. This catalyst solution was transferred to the reactor along with 3.6 ml of a 1.9 mol/l solution of triethylaluminum in toluene. The reactor was sealed, pressurized with 30 bar dry ethylene and heated to 50°C. After 120 min residence time while stirring at 1200 rpm the reaction mixture was worked up and analyzed as mentioned above. The product distribution of this example is summarized in Table 1.

The comparison shows higher activity for binuclear complexes.

Table 1. Ethylene trimerization runs

Example	Activity, kg prod./g Cr	C ₆ -Yield, wt%	C ₈ -Yield, wt%	1-hex in C ₆
1	145	88	1	99.0
2	34	89	1	99.0

Tetramerization by binuclear compounds

Example 3:

**Ethylene tetramerization using $\{[(i\text{-Pr})_2\text{N}]\text{Cr}[\mu\text{-(i-Pr)}_2\text{N}]\}_2$,
 ((phenyl)₂PN(isopropyl)P(methyl)NH(isopropyl)) and triethylaluminum**

In analogy to Example 1 a 300 ml pressure reactor was filled with 100 ml anhydrous toluene and a solution of 69.3 mg of ((phenyl)₂PN(isopropyl)P(methyl)NH(isopropyl)) (0.2 mmol) in 10 ml toluene together with 65.6 mg $\{[(i\text{-Pr})_2\text{N}]\text{Cr}[\mu\text{-(i-Pr)}_2\text{N}]\}_2$ (0.13 mmol). After adding 3.6 ml of a 1.9 M solution of triethylaluminum in toluene the reactor was sealed, pressurized with 30 bar dry ethylene and heated to 50°C. After 120 min residence time while stirring at 1200 rpm the reaction mixture was worked up and analyzed as mentioned above. The product distribution of this example is summarized in Table 2.

Comparative Example 4:

**Ethylene oligomerization using $\text{CrCl}_3(\text{tetrahydrofuran})_3$,
 ((phenyl)₂PN(isopropyl)P(methyl)NH(isopropyl)) and triethylaluminum**

In analogy to Example 1 a 300 ml pressure reactor was filled with 100 ml anhydrous toluene and a solution of 69.3 mg of ((phenyl)₂PN(isopropyl)P(methyl)NH(isopropyl)) (0.2 mmol) in 10 ml toluene together with 50.0 mg $\text{CrCl}_3(\text{tetrahydrofuran})_3$ (0.13 mmol). After adding 3.6 ml of a 1.9 M solution of triethylaluminum in toluene the reactor was sealed, pressurized with 30 bar dry ethylene and heated to 50°C. After 120 min residence time while stirring at 1200 rpm the reaction mixture was worked up and analyzed as mentioned above. The product distribution of this example is consistent with a Schulz-Flory distribution and summarized in Table 2.

Table 2. Ethylene tetramerization runs

Example	Activity, kg prod./g Cr	C ₆ -Yield, wt%	C ₈ -Yield, wt%	1-hex in C ₆	1-oct in C ₈
3	21	8	82	98.0	98.0
4	33	30	28	98.0	98.0

As can be seen from the examples, by changing the ligand utilized in the catalyst composition an easy switch from trimerization (Example 1 and 2) to tetramerization (Example 3) may be achieved. Furthermore by using binuclear chromium(II) complexes an easy switch from unselective oligomerization (Example 4) to tetramerization (Example 3) is possible.

The features disclosed in the foregoing description and in the claims may, both separately and in any combination thereof, be material for realizing the invention in diverse forms thereof.

Claims

1. Catalyst composition comprising:

(a) a binuclear chromium(II) complex;

(b) a ligand of the general structure

(A) $R_1R_2P-N(R_3)-P(R_4)-N(R_5)-H$ or

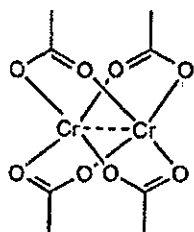
(B) $R_1R_2P-N(R_3)-P(R_4)-N(R_5)-PR_6R_7$,

wherein R_1 , R_2 , R_3 , R_4 , R_5 , R_6 and R_7 are independently selected from amino, C_1 - C_{10} -alkyl, aryl and substituted aryl, wherein the PNP- or PNPNP-unit is optionally part of a ring system, wherein at least one of the P or N atoms of structure (A) or structure (B) is a ring member, the ring being formed from one or more constituent compounds of structures (A) or (B) by substitution by formally eliminating per constituent compound either two whole groups R_1 - R_7 or H, one atom from each of two groups R_1 - R_7 or a whole group R_1 - R_7 or H and an atom from another group R_1 - R_7 , and joining the formally so-created valence-unsaturated sites by one covalent bond per constituent compound to provide the same valence as initially present at a given site; and

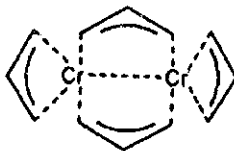
(c) an activator or co-catalyst.

2. Catalyst composition according to claim 1, wherein the chromium complex has a Cr-Cr-bond or two chromium centers are connected via a bridging ligand.

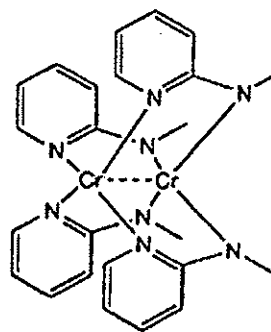
3. Catalyst composition according to any of the preceding claims, wherein the binuclear chromium complex is selected from:



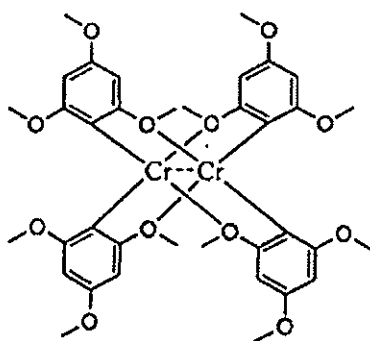
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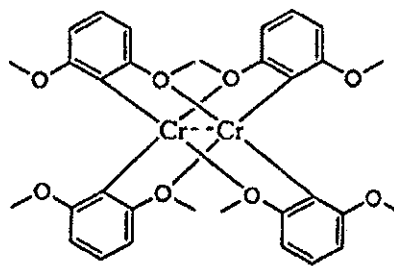
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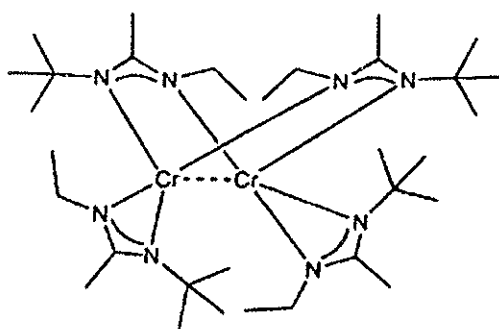
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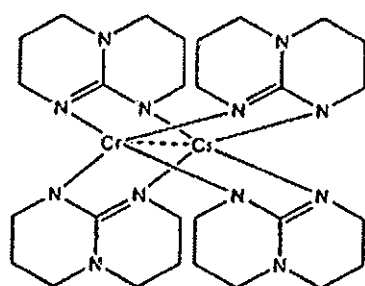
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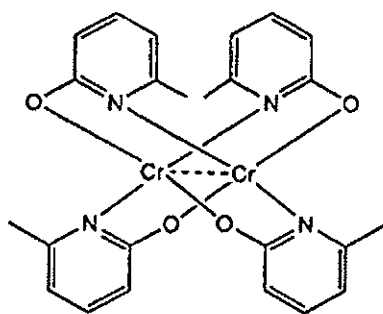
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4. Catalyst composition according to any of the preceding claims, wherein R_1 , R_2 , R_3 , R_4 , R_5 , R_6 and R_7 are selected from amino, methyl, ethyl, isopropyl, tert-butyl, phenyl, benzyl, tolyl and xylyl.

5. Catalyst composition according to any of the preceding claims, wherein the activator or co-catalyst is selected from trimethyl aluminium, triethyl aluminium, triisopropyl aluminium, triisobutyl aluminium, ethylaluminum sesquichloride, diethylaluminum chloride, ethyl aluminium dichloride, methylaluminoxane (MAO) or mixtures thereof.
6. Catalyst composition according to any of the preceding claims, wherein the ligand is selected from $(\text{Ph})_2\text{P-N(i-Pr)-P(CH}_3\text{)-N(i-Pr)-H}$, $(\text{Ph})_2\text{P-N(i-Pr)-P(Ph)-N(i-Pr)-H}$, $(\text{Ph})_2\text{P-N(i-Pr)-P(Ph)-N(Ph)-H}$, $(\text{Ph})_2\text{P-N(i-Pr)-P(Ph)-N(tert-butyl)-H}$ and $(\text{Ph})_2\text{P-N(i-Pr)-P(Ph)-N(CH(CH}_3\text{)(Ph))-H}$.
7. Catalyst composition according to any of the preceding claims additionally comprising a solvent.
8. Catalyst composition according to claim 7, wherein the solvent is selected from aromatic hydrocarbons, straight-chain and cyclic aliphatic hydrocarbons, straight-chain olefins and ethers.
9. Process for oligomerization of ethylene, comprising subjecting a catalyst composition according to any of the claims 1 to 8 to a gas phase of ethylene in a reactor and conducting an oligomerization at a temperature of from 20 to 100°C.
10. Process according to claim 9, wherein the oligomerization is carried at a pressure of 1 to 200 bar.
11. Process according to claim 9 or 10, wherein the process is carried out continuously.
12. Process according to any of the claims 9 to 11, wherein the mean residence time is from 10 minutes to 20 hours.
13. Catalyst composition, obtainable by combining at least:

(a) a binuclear chromium(II) complex;

(b) a ligand of the general structure

(A) $R_1R_2P-N(R_3)-P(R_4)-N(R_5)-H$ or

(B) $R_1R_2P-N(R_3)-P(R_4)-N(R_5)-PR_6R_7$,

Wherein R_1 , R_2 , R_3 , R_4 , R_5 , R_6 and R_7 are independently selected from amino, C_1 - C_{10} -alkyl, aryl and substituted aryl, wherein the PNP- or PNP- unit is optionally part of a ring system, as defined in claim 1; and

(c) an activator or co-catalyst.