

considered to be the most effective. In the following sections several examples will be explained according to the above theory.

If the addition takes place on β -position of monomer, the key atom exists on the chain end of growing polymer. In the case of free ionic addition the stereoregulation seems to be possible only at extremely low temperatures at which free rotations around main chain are restricted so as to maintain the most stable conformation of each carbon atom along the main chain.

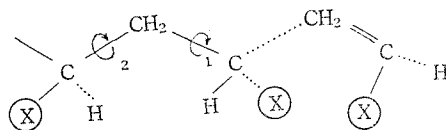


Fig. 2.

Here the trans conformation at each carbon atom may be more plausible from the viewpoint of stereochemistry and this conformation may make it possible to form the planar zigzag structure of polymer at low temperatures, wherein the two polar substituents, which are repulsive to each other, are held at their largest mutual separation, *i.e.*, syndiotactic structure (Fig. 2). Sometimes⁵⁾ the repulsion between the substituent of monomer and that of polymer chain is taken into account, but such an effect seems rather less significant because the distance between chain end and monomer is in general longer than the chemically bonded carbon-carbon distance. Moreover, the consideration on the effect arising from monomer substituent does not lead to any different conclusion from the above discussion.

Fordham *et al.*,⁶⁾ estimated the repulsion energy of polar substituent like chlorine roughly at 1 kcal./mole and concluded the predominant formation of the syndiotactic structure in the polymerization at low temperatures. In fact, experiments in free ion polymerization showed the formation of syndiotactic polymer without any exception. From these considerations it is said that there is no significant difference between radical polymerization and free ion polymerization. In the polymerization in non-polar solvent the growing polymer ion is accompanied by counter ion, which is supposed to affect more or less the conformation of the key atom rather through interaction between the substituent X in chain end and the ligand Z of counter ion as is illustrated in Fig. 3.

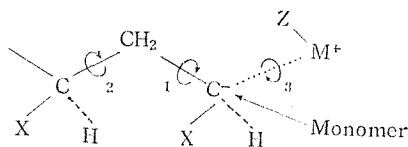


Fig. 3.

But the rotations around the bond 1 and 3, both of which can rotate independently, seem to be too free to fix X and Z in definite position, and hence stereoregulation is less effective except at low temperatures.

Theory of Multi-Coordination Centered Catalyst

The coordinated polymerization mechanism was proposed by Natta *et al.*⁷⁾ in order to explain isotactic polymerization of α -olefin by Ziegler-Natta catalyst and we adopted it to the anionic polymerization of acetaldehyde by organometallic catalyst⁸⁾. This concept is based on the assumption that the polymerization proceeds by the attack of polymer end onto monomer which is coordinated on the catalyst ion as illustrated in Figs. 4 and 5.

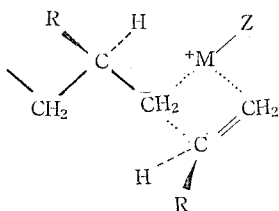


Fig. 4.

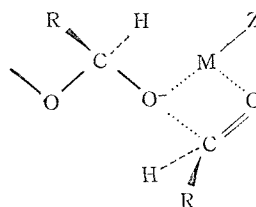


Fig. 5.

It is to be noticed that in both cases the key atom is not in polymer end but in monomer, because it is the case of α -addition in monomer, and therefore the interaction with respect to substituent relates not only to the substituent in polymer but also to the ligand attached to the catalyst. The ring formation at transition state may make it easy to form a fixed arrangement favorable for regular structure, but such a ring involving three transitory bondings may be so unstable that the effective stereoregulation cannot be expected.

Multi-coordination center hypothesis has been proposed in order to explain more efficient stereoregulation, which will be discussed with many examples.

I. MULTI-CENTER COORDINATED POLYMERIZATION WHERE A KEY ATOM EXISTS IN THE POLYMER END

The theory is based on the assumption that the catalyst possesses more than one coordination center, one of which is linked to the two polar substituents near polymer end and the other center is paired with chain end. By this way there is formed a comparatively rigid ring structure as shown in Fig. 6. If substituents are so bulky that they do not permit planar zigzag structure, the spiral may be taken. In the latter case multicentered catalyst is coordinated by adjacent polar groups in the same phase near chain end to give rise to isotactic polymerization as shown in Fig. 7.

In case of α -addition in monomer the polar groups in monomer are coordinated onto two coordination centers of catalyst. Here a rigid ring structure containing

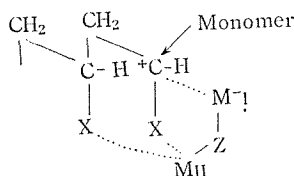


Fig. 6.

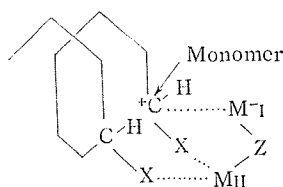


Fig. 7.

two transitory bonds is formed which may make possible the stereoregulation of key atom in monomer by the interaction between the substituent R of monomer and the ligand Y of catalyst. The rough illustration is shown in Fig. 7, whose detailed discussion will be made in the subsequent chapter.

I-1. Stereoregular Cationic Polymerization of Vinyl Ethers

In the polymerization of vinyl ethers, oxygen in ether group is capable of coordinating. If two adjacent ether groups near chain end are linked to the second catalyst center the isotactic polymer may be expected by the attack of the coordinating monomer, which adds to chain end entering from the opposite side of polymer chain (Fig. 8).

According to this there should be a complex catalyst which possesses at least two coordination centers.

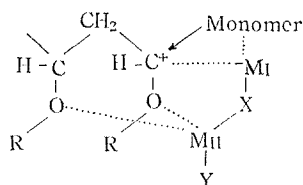
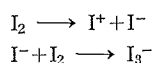
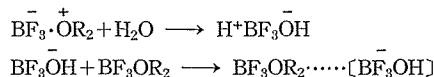


Fig. 8

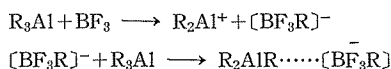
In anionic polymerization organometallic catalyst is expected to form a complex compound of this type by oxygen linkage or half-bonding. On the contrary, in cationic polymerization there had not been considered the coordination. But if the center atom in counter anion is linked with considerably electronegative ligand such as halogen or oxygen, positive formal charge on center atom may make further coordination possible. For example, iodine molecule is known to be dissociated into triiodoanion such that



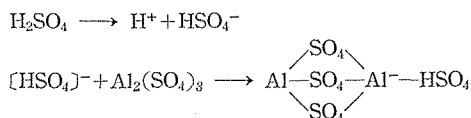
Stereoregulation in cationic polymerization of vinyl ether is known when it is conducted in conditions favoring association of catalyst, *i.e.*, at low temperatures and in non-polar solvents. Boron fluoride etherate possibly exists in associated form in suitable condition. For instance,



Many excellent catalysts are recently found in combined system of sulfuric acid—metal sulfate⁹⁾ or metal alkyl—Lewis acid¹⁰⁾. These are so active in stereoregulation that isotactic poly(vinyl ether) is produced even at room temperature. It is in contrast to the polymerization with simple Lewis acid like $BF_3 \cdot CR_2$, wherein it must be conducted at very low temperature. These systems seem to form complex anion more easily through the following mechanism:



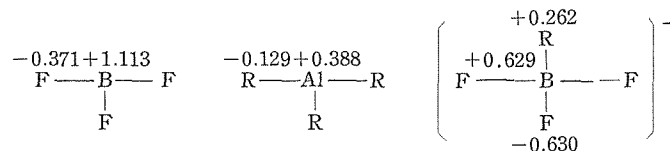
and



The complex ion resulting from combination of anion with basic molecule may act as the so-called multi-center coordination catalyst. Here, the large positive charge density of center atom in anion is expected and it may cause further coordination of another molecule. Charge density of atom may be estimated from electronegativity. For instance, in boron trifluoride the ionic character δ of B-F bond is estimated at 0.65 from their electronegativities X_F and X_B , respectively, according to Pauling's expression,

$$\delta = 1 - \exp\left\{-\frac{1}{4}(X_F - X_B)^2\right\}.$$

And hence total charge on boron will roughly be equal to 1.95, the sum of ionic character, but more correct value is to be calculated by considering feed-back effect of other boron-fluorine bonds¹¹. The following are examples of corrected charge density.



From these, alkylboronfluoride anion $[\text{RBF}_3]^-$ is known to be still acidic even toward trialkylaluminum, since positive charge density on boron of the former is larger than that on aluminum in trialkylaluminum. Therefore, the difference between both charge densities may be taken as the measure of the rough tendency toward further coordination. According to this concept the charge differences are calculated for the catalysts proposed by Nakano *et al.*¹⁰, and we found the good parallelity of stereoregulating ability of combined catalyst to the charge difference between corresponding components as summarized in Table 1.

This table seems to suggest that the combination of acidic component of Lewis acid type and metal alkyl would form a complex anion and induce the stereoregular polymerization. Catalysts consisting of one component are poor in ability to form complex, except alkyl metal sesquihalide, the latter of which was known as a catalyst of the medium regulating ability. It gave both crystalline and atactic polymers perhaps with complex active species and simple one, which existed simultaneously. The content of crystalline polymer may depend upon the content ratio as well as activity ratio of both catalyst species and may be affected by temperature, solvent and other condition. The catalyst containing metal-oxygen linkage may afford the so-called multi-center complex of excellent ability but is used in a solid form on account of poor solubility.

In this sense the concept of multi-center coordination involves adsorption on solid catalyst. In fact, these were known many excellent catalysts in solid catalyst systems.

Table 2 is made using Nakano's result¹⁰⁾, in which the possible structures assumed by us are listed additionally. These catalysts are formed by the combination of anion and neutral molecule through oxide linkage and therefore can be regarded as so-called multi-coordination catalysts. Stereoregulation is sometimes accounted for by regular adsorption of monomer¹²⁾ on solid catalyst but the multi-center concept does not always require solid state of catalyst and does not mean the regular adsorption of monomers on solid catalyst but coordination of adjacent polar groups near end in polymer chain onto multi-centered catalyst.

I-2. Anionic Polymerization of Acrylic Compounds

Polymer of acrylic compound has carbonyl as a functional group, on which multi-center coordination may be possible by complex catalyst as is illustrated in Fig. 9. Spiral structure is more probable from steric requirement (Fig. 10).

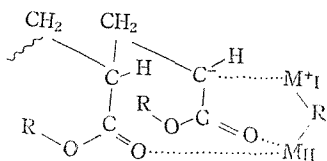


Fig. 9.

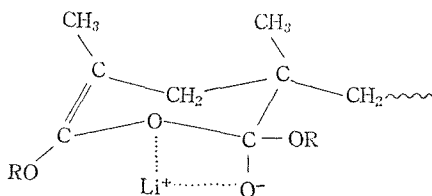
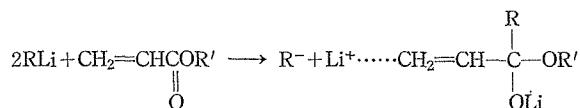
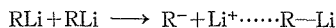
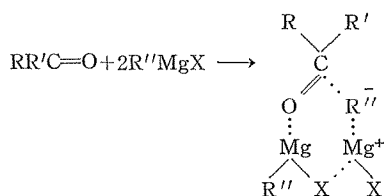


Fig. 10.

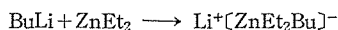
These structures are both favorable for the formation of isotactic polymer. Essentially Fig. 9 is the same as the model of Cram¹³⁾, who supposed the enolate ring structure paired with lithium cation (Fig. 10). On the other hand a spiral structure was proposed by Glusker¹⁴⁾. Both authors seem to try to explain the stereoregulation by lithium cation, and in these cases the associated catalyst seems to be more favorable for suitable arrangement of monomer, because simple lithium cation has not so large ability to coordinate three atoms. Moreover the distance between lithium cation and key atom seems to be too long to contribute to stereoregulation. In fact, alkyllithium was reported to afford more crystalline polystyrene as it was used in higher concentration or in more associated state¹⁵⁾. Lithium cation may afford crystalline polymer when it is in associated form or complex form as



The addition of Grignard's reagent to carbonyl compound is known to proceed through a cyclic transition state, which consists of two moles of reagent. The transition structure is very similar to the above complex.



Many complex type catalysts consisting of two kinds of metal alkyls or metals were investigated whereby the so-called "At-Komplex" is formed, e.g.,



Many suitable groups of catalyst for methacrylate polymerization were found which are listed in Table 3 and Table 4. Results are rather complicated but Table 3 may lead to some conclusion that isotactic-forming ability increases as p-character of the cation becomes larger in the order of $\text{Na} < \text{Li} < \text{Ba} < \text{Sr}$ and as the anion complex involves more hydrogens instead of alkyl groups in the order of $\text{R}_n < \text{HR}_{n-1} < \text{H}_m\text{R}_{n-m} < \text{H}_n$. This fact seems to correlate to the complex formation by half bonding such as

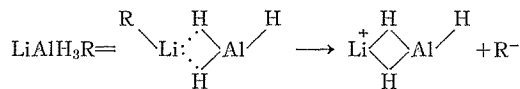


Table 3.

Type of crystalline poly(methyl methacrylate)	Combination of metal and alkyl metal and At-Complex resulted
Isotactic	$\text{LiAlH}_4 + \text{Et}_2\text{Zn} \longrightarrow \text{LiAlH}_{4-n}\text{R}_n + \text{Zn} + \text{RH}$
	$\text{LiAlH}_4 + \begin{cases} \text{Et}_2\text{Cd} \\ \text{Et}_3\text{Al} \\ \text{Bu}_3\text{B} \\ \text{Bu}_2\text{Hg} \end{cases}$
	$\text{Ba} + \text{Et}_2\text{Zn} \longrightarrow \text{BaZnEt}_4 + \text{Zn}$
	$\text{Sr} + \text{Et}_2\text{Zn} \longrightarrow \text{SrZnEt}_4 + \text{Zn}$
Stereoblock	$\text{Li} + \text{Et}_2\text{Zn} \longrightarrow \text{LiZnEt}_3 + \text{Zn}$
	$\text{Na} + \text{Et}_2\text{Zn} \longrightarrow \text{NaZnEt}_3 + \text{Zn}$
	$\text{LiH} + \text{Et}_2\text{Zn} \longrightarrow \text{LiZnHEt}_2$
	$\text{NaH} + \text{Et}_2\text{Zn} \longrightarrow \text{NaZnHEt}_2$
	$\text{LiH} + \text{Et}_3\text{Al} \longrightarrow \text{LiAlHEt}_3$
	$\text{NaH} + \text{Et}_2\text{Cd} \longrightarrow \text{NaCdHEt}_2$

Table 4.

Anion*	Cation			
	Sr	Ba	Li	Na
MH_n			LiAlH_4	
$\text{MH}_m\text{R}_{n-m}$			LiAlH_3R LiAlH_2R_2	
MHR_{n-1}			LiAlHEt_3 LiZnHEt_2	NaZnHEt_2 NaCdHEt_2
MR_n	SrZnEt_4	BaZnEt_4	LiZnEt_3	NaAlEt_4 NaZnEt_3
	Isotactic		Stereoblock	Atactic

* M means metal.

Theory of Multi-Coordination Centered Catalyst

wherein half bonding can exist when one cationic metal is divalent and of larger p-character like Li, Ba, Sr or Ca and the bridging atom is hydrogen or alkyl of small size like methyl. Since alkyl anion is more stable than hydride anion, the replacement of hydrogen by alkyl may enhance the tendency of the alkyl anion formation but it makes the bridge formation more difficult. At least two hydrogen atoms must be left unreplaced for the bridge formation.

The ease of the complex counter ion formation for several anionic catalysts has been calculated in the same manner as adopted for cationic catalyst systems. It is assumed that in each binary catalyst system, one component is the anionic source and that the counter cation of the anionic species formed from the anionic source is coordinated to the other component to give the multi-center cation. In Table 5, the calculation results are compared with the stereoregulating abilities of these catalytic systems observed for anionic polymerization of butyl acrylate. Here also the concept of multi-centered coordination seems to be satisfactory. Investigation on other monomers related to methyl methacrylate as follows indicates the effects of groups attached to key atom¹⁰.

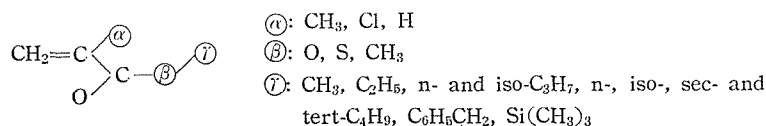


Table 5. Charge density in ion—molecule complex.

No.	Catalyst system	R.A.	Cation	e_O	Molecule	e_M	$e_O - e_M$
1	C₆H₅MgBr	+	R-Mg ⁺	+0.99	MgBr ₂	+0.6963	0.2937
2	n-BuLi	+	Li ⁺	+1.00	R-Li	+0.4200	0.5800
3	Et ₃ Al-n-BuLi	††	Li ⁺	+1.00	R ₃ Al	+0.3882	0.6118
4	Et ₂ Cd-n-BuLi	††	Li ⁺	+1.00	R ₂ Cd	+0.2222	0.7778
5	Ca-ZnEt ₄	‡‡‡	R-Ca ⁺	+1.07	R ₂ Zn	+0.2667	0.8033
6	Sr-ZnEt ₄	‡‡‡	R-Sr ⁺	+1.07	R ₂ Zn	+0.2667	0.8033

Assumed active species (bold-faced) for each catalyst system :

- No. 1 (C₆H₅)₂Mg·MgBr₂ → C₆H₅⁻ + [C₆H₅Mg]⁺[MgBr₂]
 No. 2 2(n-BuLi) → n-Bu⁻ + Li⁺[n-BuLi]
 No. 3 LiAlEt₃(n-Bu) → n-Bu⁻ + Li⁺[AlEt₃]
 No. 4 LiCdEt₂(n-Bu) → n-Bu⁻ + Li⁺[CdEt₂]
 No. 5 CdZnEt₄ → Et⁻ + [EtCa]⁺[ZnEt₂]
 No. 6 SrZnEt₄ → Et⁻ + [EtSr]⁺[ZnEt₂]

The conclusions are such that :

1. When α is equal to H, *i. e.*, acrylate *etc.*, bulky γ group such as iso-C₃H₇, sec- and tert-C₄H₉, seems to favor stereoregulation. And this fact suggests that the bulky group would control the free rotation in main chain and would effectuate the rigid regular conformation in main chain as far as bulkiness does not go over the limit value at which steric hindrance becomes too large.

2. Stereoregulation tends to decrease as α group becomes bulkier and α -methyl derivative affords crystalline polymer only when γ is methyl, and α -chlorine derivative does so when γ is sec-butyl and β is sulfur.

3. Thiol esters, when β is sulfur, are stereoregulated more easily and this property seems to be attributed to the enhancement of coordination at carbonyl by sulfur atom of less electronegativity.

II. STEREOREGULATION OF THE KEY ATOM PRESENTING IN MONOMER

This type of stereoregulation may be expected in anionic polymerization of aldehyde and alkylene oxide. Ziegler-Natta's coordinated anionic polymerization is also of this kind in a wide sense. Since the key atom is present in monomer, stereoregulation may be conducted by interaction of the substituent of monomer with the ligand on catalyst or with the substituent of polymer end. According to multi-center coordination concept the following models seem to be probable (Figs. 11 and 12).

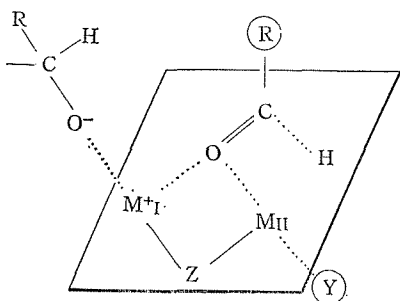


Fig. 11.

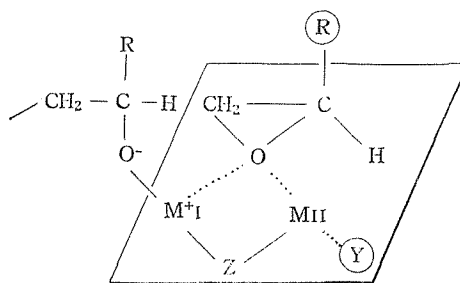


Fig. 12.

A monomer coordinating to two centers of catalyst maintains the definite position against polymer end and catalyst. Hence the substituent R possesses the characteristic position against that of ligand Y and this may induce the successive addition of the same configurations, and results in the formation of the isotactic structure. On the contrary, possible structures rendered by coordination of simple counter ion seem to be less stable and therefore less probable, because free rotation in coordination bond is not prohibited completely (Figs. 13 and 14). Even if there is assumed a ring structure, consisting of monomer, polymer and catalyst it may not be enough stable, because it contains three transitory bonds (Figs. 15 and 16).

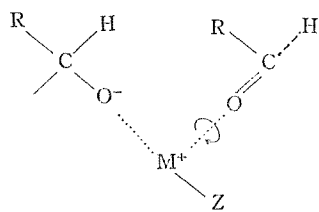


Fig. 13

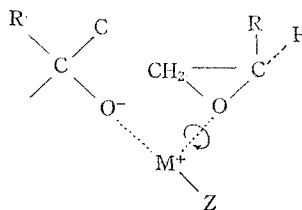


Fig. 14.

Theory of Multi-Coordination Centered Catalyst

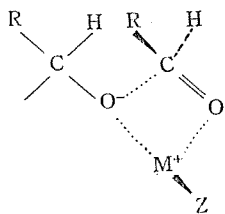


Fig. 15.

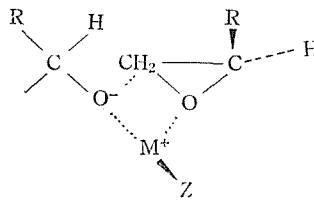
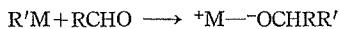


Fig. 16.

In the case of alkylene oxide, the stereoregulation is effected by selective coordination of *d*- or *l*-isomer on catalyst, depending on the nature of ligand Z.

II-1. Anionic Polymerization of Acetaldehyde

Acetaldehyde and related aldehydes were found to polymerize by use of metal alkyl¹⁷⁾ and aluminum oxide¹⁸⁾ as catalyst, the former catalyst gave crystalline polymer and the latter catalyst amorphous¹⁸⁾ one. Lewis acid type catalyst was also reported to afford atactic polymer of acetaldehyde¹⁹⁾. Metal alkyl may convert into metal alkoxide by the reaction with aldehyde prior to polymerization.



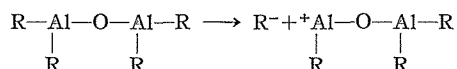
In fact, metal alkoxides prepared from various alcohols were found to have similar

Table 6.

Catalyst	Possible structure	Stereoregularity
Metal alkyl (reacted with aldehyde)		Isotactic and atactic
Metal alkoxide		Isotactic and atactic
Partly-hydrolyzed metal alkyl		Stereoblock
Partly-hydrolyzed metal alkoxide		Stereoblock
Metal oxide		Atactic

activity. Furthermore, metal alkyl and metal alkoxide are found to be activated by partial hydrolysis, whereby alkyl metal oxide may be actual catalyst. It is interesting that partly-hydrolyzed catalyst can afford stereoblock polymer. Table 6 shows the various catalyst and their possible structure.

From Table 6 it is concluded that active catalyst is used to have a linkage of metal-oxygen, which seems to be favorable for formation of multicenter catalyst, *e. g.*,



Complex cation of $\text{RAlO}_{1/2}-\text{R}_2\text{AlO}_{1/2}$ structure may thus be formed.

Alumina, on the other hand, does not afford crystalline polymer but atactic on despite its metal-oxygen linked structure.

The lack of stereoregulating ability of alumina is somewhat queer, but there seems to be the possibility of cationic polymerization because aluminum oxide acts often as Lewis acid. Replacement of alkyl groups by aluminum-oxygen linkage may make the compound more acidic because of the increase of positive charge density on aluminum atom as is shown in Table 7.

Table 7.

R_3Al	+0.3882	R_2Zn	+0.2667
$\text{R}_2-\text{Al}-\text{O}-\text{Al}-\text{R}_2$	+0.5385	$\text{R}-\text{Zn}-\text{O}-\text{Zn}-\text{R}$	+0.4538
$\begin{array}{c} \text{R}-\text{Al}-\text{O}-\text{Al}-\text{R} \\ \quad \\ \text{OR} \quad \text{OR} \end{array}$	+0.7838	$-\text{O}-\text{Zn}-\text{O}-$	+0.6824
$\begin{array}{c} -\text{O}-\text{Al}-\text{O}-\text{Al}-\text{O}- \\ \quad \\ \text{O} \quad \text{O} \\ \quad \end{array}$	+0.9219	$\text{RO}-\text{Zn}-\text{O}-\text{Zn}-\text{OR}$	+0.7616
$\begin{array}{c} \text{RO}-\text{Al}-\text{O}-\text{Al}-\text{OR} \\ \quad \\ \text{OR} \quad \text{OR} \end{array}$	+1.0186	$\text{RO}-\text{Zn}-\text{OR}$	+0.8196
$\begin{array}{c} \text{RO}-\text{Al}-\text{OR} \\ \\ \text{OR} \end{array}$	+1.0517		

II-2. Coordinate Anionic Polymerization of Propylene Oxide

Polymerization of alkylene oxide is very similar to that of acetaldehyde. They are polymerized by common catalysts. It was found that diethylzinc was much enhanced in activity when it was treated with an almost equimolar amount of water. Dialkylzinc oxide or its homologue may be the actual catalyst which affords polymer containing less soluble crystalline portion, although its content does not exceed thirty percent. Two types of active species may be present, which are assumed to be the simple zinc alkoxide and the complex alkylzinc oxide; the former affords atactic polymer and the latter crystalline one. Coordinate anionic mechanism is assumed from the finding that the polymer contains the alkoxy

Theory of Multi-Coordination Centered Catalyst

fragment arising from the catalyst. The catalyst is made from dibutylzinc treated with alcohol, whereby 9,10-anthracene dimethylol is used and detected by ultraviolet analysis. Moreover, optically active poly(propylene oxide) was obtained by asymmetric induction from *dl*-monomer, when the diethylzinc activated with (+) borneol or (-) menthol is used as the catalyst (Table 8).

Table 8. Asymmetric induction in polymerization of propylene oxide.

Activator	Solvent for polymer	η_{sp}/C	$[\alpha]_D$ of polymer	
			in benzene	in chloroform
(+) Borneol	Toluene	5.63	-5.9°	+7.4°
(+) Borneol	Hexane	3.30	-4.9°	+6.1°
(+) Borneol	Benzene	3.65	-3.7°	+2.5°
(-) Menthol	Benzene	0.59	-3.6°	+4.2°

Polymerization: Propylene oxide, 0.5 mole; solvent, 30-35 ml.; at 80°C.; at conversion, 17-30%.

Catalyst: Diethylzinc, 0.025 mole; alcohol, 0.05 mole.

Polymer: Crystalline fraction, ca. 10% except for (-) menthol (2.7%).

Optical rotation: Measured in 1-3% solutions at 10-15°C.

Here, the optical rotation of polymer is proved to arise not from alcoholic fragment attached to polymer but from polymer configuration, because rotation is too large to be regarded as the fragment effect and besides inversion of rotation is found in different solvents, in agreement with the results reported by Price²¹, who prepared *l*-polymer from *l*-propylene oxide.

It is still a question how asymmetric induction takes place, either direct induction by catalyst ligand to polymer chain or indirect induction through chain. In the latter case asymmetric induction may be caused by alkoxide anion but further regulation is caused by the successive induction by the penultimate unit. However, the neighboring asymmetric centers seem to be too far apart from each

Table 9. Crystalline fraction in polypropylene oxide prepared by the system of dibutylzinc and alcohols.

(Monomer, 0.05 mole; solvent, 3.5 ml. toluene; catalyst, 0.0023 mole Bu_2Zn ; cocatalyst, 0.0046 mole alcohol; polymerization, room temp.)

Alcohol	Polymer yield (%)	Crystalline fraction (%)
CH_3OH	68	9.2
$\text{C}_2\text{H}_5\text{OH}$	51	5.3
<i>n</i> - $\text{C}_3\text{H}_7\text{OH}$	85	2.8
<i>iso</i> - $\text{C}_3\text{H}_7\text{OH}$	trace	—
<i>n</i> - $\text{C}_4\text{H}_9\text{OH}$	93	1.6
<i>iso</i> - $\text{C}_4\text{H}_9\text{OH}$	33	15.1
<i>sec</i> - $\text{C}_4\text{H}_9\text{OH}$	trace	—
<i>tert</i> - $\text{C}_4\text{H}_9\text{OH}$	nil	—

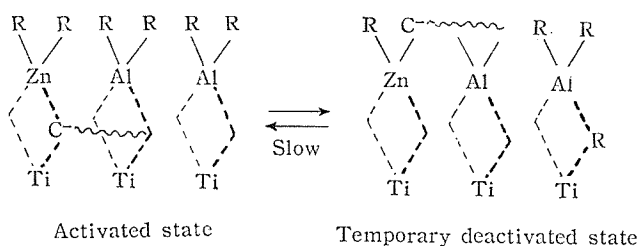


Fig. 19.

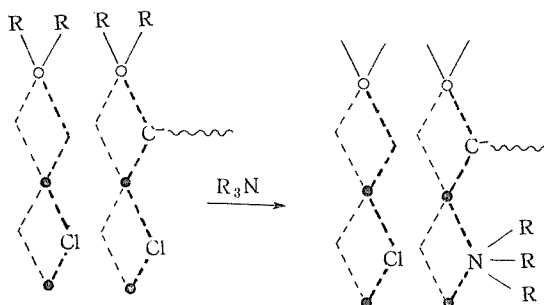


Fig. 20.

IV. CIS AND TRANS POLYMERIZATION OF DIOLEFIN

There are two types of addition for conjugated diolefin, *i. e.*, 1,4- and 1,2(or 3,4-) additions. Stereochemically 1,4-polymer is classified into *cis*- and *trans*-forms and 1,2-polymer into *syndio*- and *iso*-tactic configurations. *Cis*-polyisoprene and *cis*-polybutadiene are very important from industrial view-point. They are successfully prepared by use of lithium catalyst or modified Ziegler catalyst but they are not the same in catalytic selectivity. Lithium or alkyl lithium is known to be suitable for *cis*-polymerization of isoprene but not for butadiene, the latter of which has been reported to be successful by use of modified Ziegler type catalyst containing cobalt or nickel salt or titanium iodide as component in contrast to undesired result in isoprene.

In the case of diolefin stereoregulation is concerned with the reaction form of monomer in itself. Stearns²⁵⁾ proposed cyclic mechanism for monomer conformation for accounting for lithium-catalyzed *cis*-polymerization of isoprene (Fig. 21). But he did not elucidate the reason why butadiene did not afford *cis*-polymer. I rather prefer the mechanism through two-point coordination with respect to monomer as shown in Figs. 22 and 23.

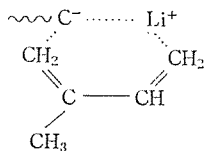


Fig. 21.

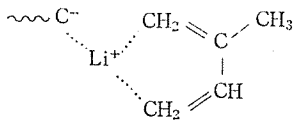


Fig. 22.

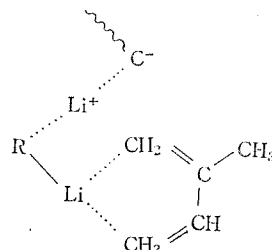


Fig. 23.

Theory of Multi-Coordination Centered Catalyst

Modified Ziegler catalyst is available for cis-polymerization of butadiene, whereby iron group such as iron, cobalt and nickel halide or related compounds are used and this fact agrees dimensionally with the complex formation of the above type as indicated in Fig. 24.

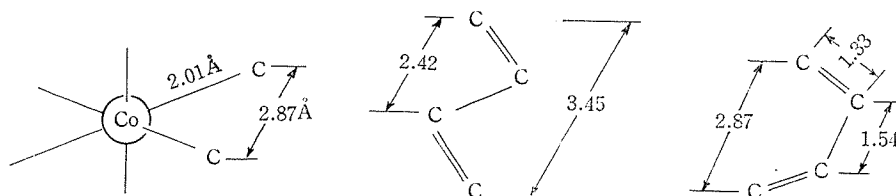


Fig. 24.

Table 10 illustrates the lengths of metal—carbon bond and the distances between two carbons adjacent to each other.

Table 10.

Metal	Radius of metal (Å)	Length of metal-carbon bond (Å) ^{a)}	Distance between carbon-carbon (Å) ^{b)}
Cu	1.28	2.05	2.90
Zn	1.38	2.15	3.04
Ti	1.45	2.22	3.15
V	1.36	2.13	3.01
Cr	1.28	2.05	2.90
Mn	1.31	2.08	2.94
Fe	1.27	2.04	<u>2.88</u>
Co	1.26	2.03	<u>2.87</u>
Ni	1.24	2.01	<u>2.84</u>
Li	1.57	2.34	<u>2.34^{c)}</u>

^{a)} Radius of carbon is estimated to be 0.77 Å.

^{b)} Bond angle is estimated to be 90°.

^{c)} Bond angle is estimated to be 60° for <Li-C-Li of halfbonded complex.

The table shows that only cobalt, nickel and iron have suitable carbon—carbon distance for coordination, when 1,4-distance of cis-diolefin is estimated to be 2.78 Å.

From Pauling's concept of electronegativity the bond length is closely correlated to the electronegativities of metal and linked atom and it is much shortened in polar bond. For the same reason, metal linked with hetero-atoms of large electronegativity has partial positive charge and therefore the length of carbon-metal bond to be formed by further coordination is shortened according to the ionicity (charge density) of metal.

Based on this assumption, the charge density of metal halides are calculated as listed in Table 11, where it is concluded that metals having moderate charge density, *e. g.*, titanium iodide, nickel or cobalt chloride seem to be suitable for cis-addition, whereas strongly polarized metal salts, *e. g.*, titanium and vanadium chloride etc., indicate rather 1,2- or trans-addition. For isoprene the suitable

Table 11. Charge density on catalyst component.

Catalyst component	Charge density	Butadiene	Isoprene
TiI ₄	0.22	Cis (86%)	—
NiCl ₂	0.30	Cis (97%)	Poorly active
CoCl ₂	0.30	Cis (87%)	Poorly active
TiBr ₄	0.34	Cis (75%)	Poorly active
CrCl ₃	0.39	1, 2	Inactive
TiCl ₄	0.42	Trans	Cis (>95%)
RLi	0.42	Trans and cis	Cis (>95%)
MnCl ₃	0.42	1, 2	1, 2
RNa	0.47	1, 2	1, 2 and 3, 4
Ti(OBu) ₄	0.63	Trans	—
VCl ₃	0.39	Trans	Trans

ionicity of metal seems to lie in stronger region and titanium iodide is too weak for polymerization. Steric hindrance of methyl group in isoprene may require larger positive charge of catalyst metal for coordination. Fig. 25 shows one set of hypothetical models accounting for cis and other polymerization, where it is assumed that as the distance between two neighboring positions for coordination becomes small, the structure becomes favorable for cis-, trans- and 1,2-addition according to the order, whose suitable distances are estimated at 2.87 Å (cis), 2.42 Å (1,3 distance for trans form) and less than 2.42 Å (1,2-addition), respectively. Here a complex catalyst having two coordination centers, *i. e.*, metal alkyl—metal salt combination, which dissociates ionically to induce anionic polymerization and

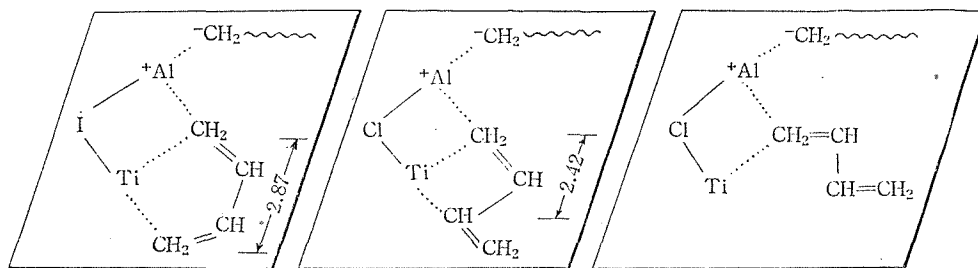


Fig. 25.

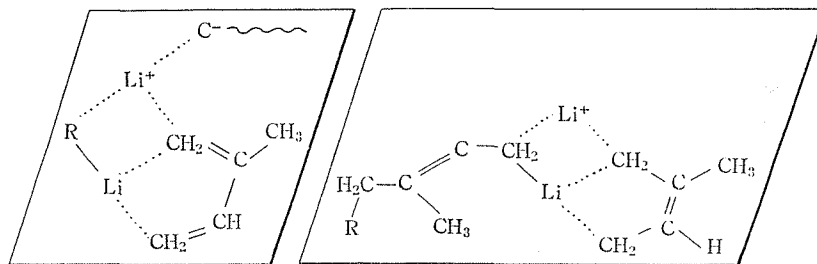


Fig. 26.

Fig. 27.

the counter cation combined with metal salt may play stereospecific regulation of monomer coordinated with metal salt component. Single cation does not explain stereoregulation and Lewis acid alone does not initiate anionic polymerization. Cis-addition of isoprene may be accounted for by assuming the associated form of alkyl lithium or isoprene-alkyl lithium adduct (Figs. 26 and 27).

CONCLUSION

In this article it is emphasized that the catalysts having two coordination centers would be favorable for stereoregulation; one center is counter ion and the other center is linked with ion by half-bonding, oxide linkage and ion-molecule linking through coordination. The first center is paired with polymer chain end by forming ion pair and the second center regulates free rotation in chain end by coordination with two adjacent polar substituents for polymerization of vinyl compounds. In the case where the key atom is present in monomer such as aldehyde, alkylene oxide, α -olefin and diolefin, one or two positions of monomer are linked with two coordination centers of catalyst, whereby stereoregulation can be effected by the ligand of catalyst. Finally, cis-addition in diolefin is explained by suitable 1,4-coordination with catalyst center. Of course, the stereoregulation in polymerization is so complicated that inquisitive discussion without further experiments is rather harmful, but the so-called multi-center coordination concept seems often to be helpful for consideration of stereoregulation.

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