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ARTICLE TYPE

## Dinuclear salen Cobalt complex incooperated Y(OTf)<sub>3</sub>: Enhanced enantioselectivity in hydrolytic kinetic resolution of epoxides

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The activation of inactive Jacobsen chiral salen Co(II) (salen = *N,N'*-bis(3,5-di-*tert*-butylsalicylidene)-1,2-cyclohexane-diamine) compound is attained by dinuclear chiral salen Co(III)-OTf complex formation with yttrium triflate. The yttrium metal not only displayed the promoting effect in the electron transfer reaction, but also it assisted to form two stereocentres of Lewis acid complex with Co(III)-OTf. We found that the binuclear Co-complex significantly enhanced reactivity and enantioselectivity in the hydrolytic kinetic resolution of terminal epoxides compared to its monomer analogous and kinetic data is also consistent with these results.

Chiral salen metal complexes proved as potential catalysts in various asymmetric syntheses.<sup>1-4</sup> Catalytic asymmetric ring opening of racemic terminal epoxides with water (Hydrolytic Kinetic Resolution, HKR) using Jacobsen's chiral (salen)Co<sup>III</sup>-OAc complex as chiral catalyst has been widely applied and highly efficient for the preparation of enantioenriched epoxides in academic and industrial sector.<sup>5-6</sup>

The catalytically inactive chiral salen Co<sup>II</sup> complex is activated by aerobic oxidation *via* one electron transfer reaction to get chiral salen Co<sup>III</sup> complex promoted by many Brønsted acids, which was mechanistically found to exhibit second order dependence on salen [Co<sup>III</sup>] catalyst unit routed through cooperative bimetallic mechanism.<sup>7-8</sup> The metal valence change from Co<sup>III</sup> to Co<sup>II</sup> during HKR of racemic epoxides has been studied in detail.<sup>9</sup> Further, The high reactivity, recyclability and DFT calculation of counter ion/axial ligand linked to monometallic salen Co<sup>III</sup> unit has also been demonstrated including triflate ion.<sup>10</sup>

Recently, we have developed the dinuclear chiral salen Co complex bearing Lewis acids of different salts of Al, Ga, In and Tl which showed very good chiral catalyst in asymmetric ring opening and closing reactions.<sup>11</sup>

In continuation of our interest in activation and developing of dinuclear chiral salen complex, herein reporting the synthesis and application of functional dinuclear salen Co<sup>III</sup> complex (Fig. 1). Interestingly, the Y(OTf)<sub>3</sub> not only works as a linker, but also cooperatively activates the incoming nucleophiles and thus reduce the barrier heights in the HKR reaction of racemic terminal epoxides, which ultimately provides enhanced activity and enantioselectivity to its monomer analogous. The monometallic and bimetallic chiral salen Co linked with Y(OTf)<sub>3</sub> can be prepared by reacting the chiral salen Co<sup>II</sup> and Y(OTf)<sub>3</sub> with mole ratio of 1:1.33 and 2:1.66 respectively in THF solvent at room temperature and open atmosphere for 40 minutes. After completion of reaction the solvent was removed by rotary evaporation and crude green solid residue was obtained and dried. The dried crude green solid was dissolved in CH<sub>2</sub>Cl<sub>2</sub> and washed by H<sub>2</sub>O at least three times. After concentration and evaporation of separated CH<sub>2</sub>Cl<sub>2</sub>, afforded dark green solid powder (m. p. > 380°C) Yield = 98-99 %. The chiral salen (*R,R*)-(-)-*N,N'*-bis(3,5-di-*tert*-butylsalicylidene)-1,2-cyclohexane diamino cobalt (II) (Fig. 1) and Y(OTf)<sub>3</sub> (purity= 98%) were procured from Aldrich and used as such.

The continuous monitoring for the formation of oxidized salen Co dinuclear complex (Fig. 2) and quantitative estimation were performed by UV-vis spectroscopy by using the following equations.<sup>12</sup>

$$\epsilon_{\text{Co}^{\text{II}}_{359}} \text{ nm} \times [\text{Co}^{\text{II}}]_{\text{t}} + \epsilon_{\text{Co}^{\text{III}}_{359}} \text{ nm} \times [\text{Co}^{\text{III}}]_{\text{t}} = \text{Abs}_{,359 \text{ nm}} \quad \text{Eq. 1}$$

$$\epsilon_{\text{Co}^{\text{II}}_{419}} \text{ nm} \times [\text{Co}^{\text{II}}]_{\text{t}} + \epsilon_{\text{Co}^{\text{III}}_{419}} \text{ nm} \times [\text{Co}^{\text{III}}]_{\text{t}} = \text{Abs}_{,419 \text{ nm}} \quad \text{Eq. 2}$$

$$[\text{Co}^{\text{II}}]_{\text{t}} + [\text{Co}^{\text{III}}]_{\text{t}} = [\text{Co}^{\text{II}}]_0 \quad \text{Eq. 3}$$

The value of  $\epsilon$  for the characteristic peak of salen Co<sup>II</sup> were calculated to be  $1.168 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$  at 359 nm and  $1.209 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$  at 419 nm by taking various concentration of salen Co<sup>II</sup> complex and using linear regression method whereas for salen Co<sup>III</sup> we have calculated using numerical method based on the

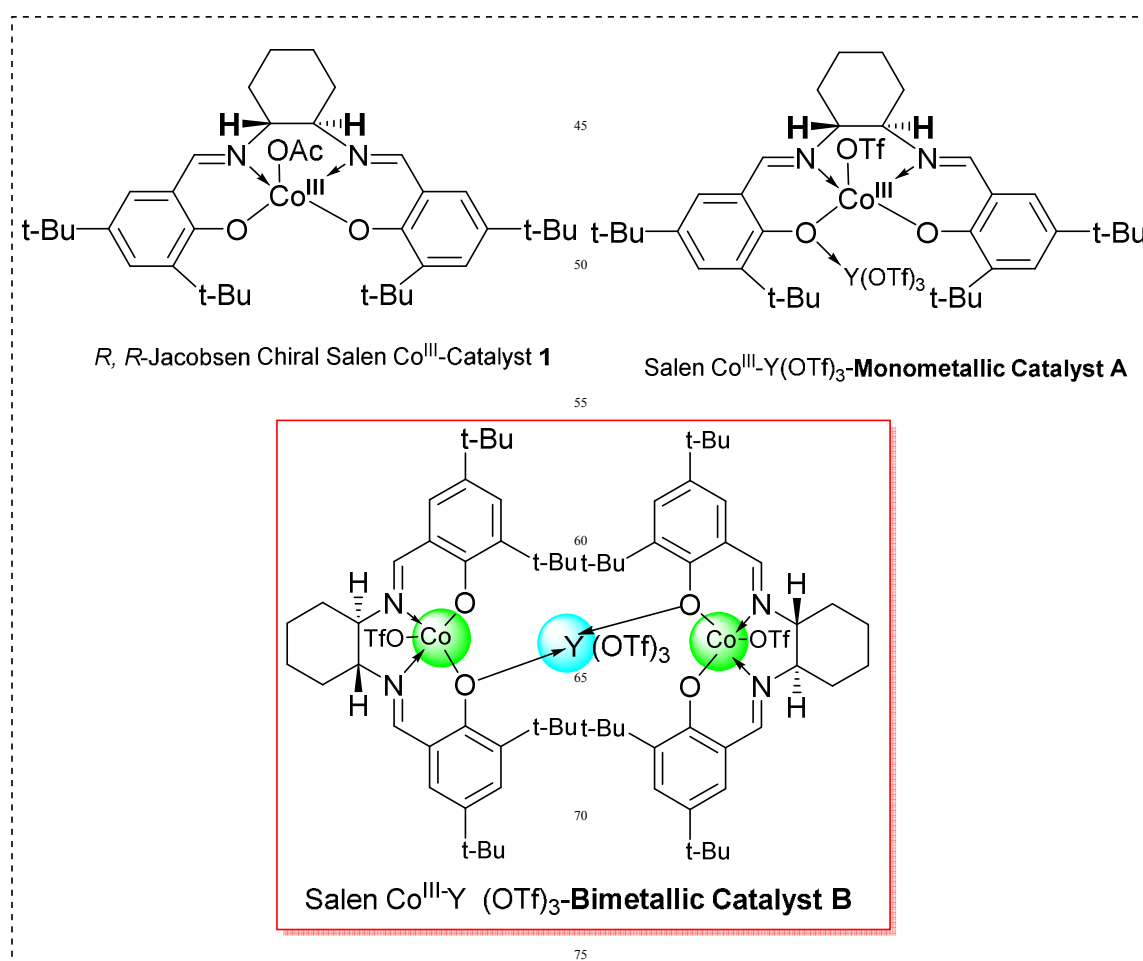
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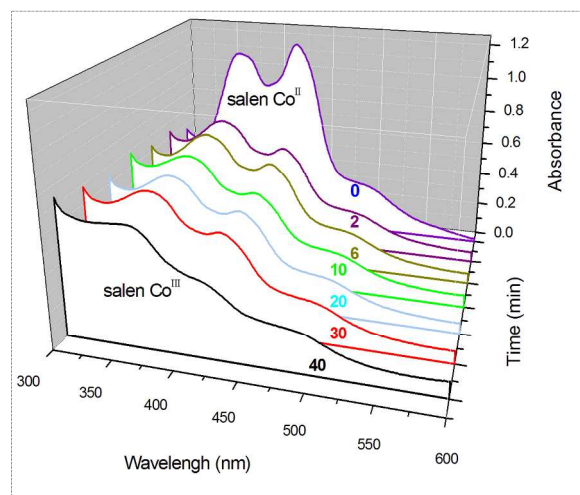
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**Fig. 1** Structure of monomer and dimer salen Co complex

UV-vis spectrum of salen Co<sup>II</sup> and salen Co<sup>III</sup> in different concentrations of these reactions with the help of above mentioned equations. We observed that there is complete conversion of salen Co<sup>II</sup> to salen Co<sup>III</sup> and the disappearance of characteristic peak at 419 nm of salen Co<sup>II</sup> (see kinetic profile ESI Fig S6).



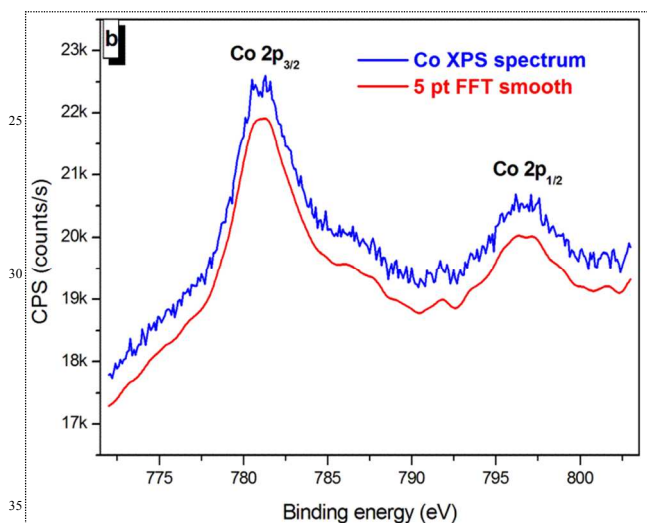
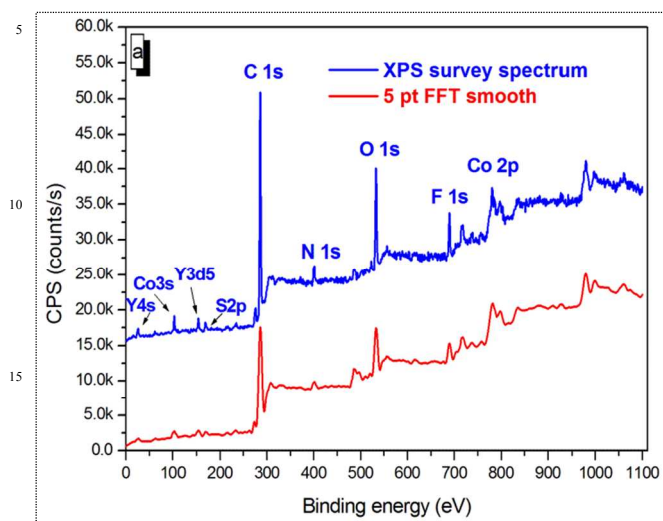
**Fig. 2** Monitoring of continuous UV-vis spectra for the formation of chiral [salenCo-OTf]<sub>2</sub>Y(OTf)<sub>3</sub> dimer.

The full range general XPS survey data provides valence states of elements and very useful structural information of bimetallic salen Co bearing Y(OTf)<sub>3</sub> shown in Fig 3a. The oxidation state of cobalt (III) in bimetallic salen catalyst B was further confirmed by Co 2p XPS spectrum where its binding energy of Co 2p<sub>3/2</sub> increases with the increase in the formal oxidation state of the cobalt ion.<sup>13</sup> It shows a Co 2p<sub>3/2</sub> and Co 2p<sub>1/2</sub> core level peak at a binding energy of 780.5 and 796.2 eV respectively (Fig 3b) without exhibiting any complex satellite peak always observed in the Co(II) 2p spectra. The spin-orbit splitting is found to be 15.7 eV, indicates the Co (III) oxidation state which is similar to the reported literature.<sup>13</sup> The slight shifting of binding energy peak might be possibly due to the difference in coordination environment of salen ligand oxygen which is coordinated to Y(OTf)<sub>3</sub> (Fig. 1). In general, analysis of the XPS survey data of bimetallic catalyst B revealed the presence of significant peaks associated with carbon (1s = 285 eV), nitrogen (1s = 400 eV), oxygen (1s = 532 eV), fluorine (1s = 689 eV), cobalt (3s = 106 eV), yttrium (4s = 42 eV; 3d5 = 154 eV) sulphur (2p = 169 eV, 2s = 230 eV) (Fig. 3a)

<sup>19</sup>F NMR confirms the presence of OTf, shows the chemical shift at  $\delta = -62.70$ ;  $-191.63$  and  $-62.70$ ;  $-170.93$  and  $-191.63$ . The <sup>1</sup>H, <sup>13</sup>C NMR, XRD, HRMS and FTIR support the formation of complex A and B (see ESI).

The catalytic activities of the salen Co-complex A and B were evaluated in the HKR of terminal epoxides and results were summarized in Table 1. The loading of the monomer A and

binuclear **B** catalyst were based on per [Co] salen unit. All HKR reactions were performed under solvent free conditions except for epoxides with aryl ether (entry 7 and 8). Entry 2 of propylene



**Fig. 3** (a) XPS survey data of the bimetallic salen Co-Y(OTf)<sub>3</sub> catalyst (b) Co 2p high resolution region.

epoxide shows highest reactivity among the examined epoxides, afford >99% ee in short time (1.5h). Overall obtained results with rest of epoxides, demonstrate that the chiral salen Co dimeric complex **B** catalyzed HKR of various terminal epoxides containing functionalities of chloro, ether, ester and aliphatic, have been shown good to excellent enantioselectivity (>97-99% ee) except the compound 2-naphthyl glycidyl ether (entry 8).

On the contrary, the analogous monometallic salen Co catalyst **A** showed less reactivity and selectivity in comparison to its dimeric catalyst **B**. All the epoxides taken in the present study the  $k_{rel}$  were also observed high enough which led to enhanced enantioselectivity for the recovered epoxides and diol products.

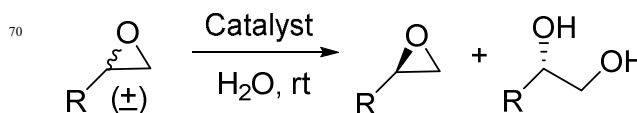
To elucidate the higher reactivity and enantioselectivity of the dimer catalyst **B** the kinetic study of epichlorohydrin (ECH) was

performed and it showed the two term rate equation involving both intra- and intermolecular reaction (eq 4)<sup>11b,14</sup>

$$\text{Rate} \propto k_{\text{intra}} [\text{catalyst}] + k_{\text{inter}} [\text{catalyst}]^2 \quad \text{Eq. 4}$$

plots of rate/[catalyst] vs. [catalyst] provides linear with slopes equal to  $k_{\text{inter}}$  and y-intercepts corresponding to  $k_{\text{intra}}$  with positive value for dimer catalyst **B** i. e.  $36.3 \text{ M}^{-1} \times \text{min}^{-1}$  and  $68.0 \times 10^{-2} \text{ min}^{-1}$  respectively. The monomeric catalyst **A** provided y-intercepts of nearly zero, revealing the absence of any first-order pathway in this HKR reaction (Fig. 4). These results are more

Table 1 : HKR of terminal epoxides catalyzed by the mono and bi-metallic catalyst **A** and **B**<sup>a</sup>



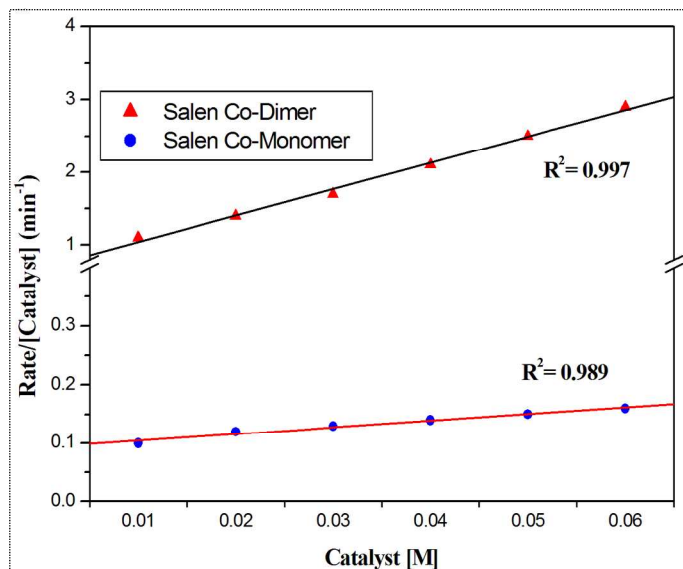
Entry	Epoxides	Catal. Type <sup>b</sup>	Time (h)	ee of recovered epoxides (%) <sup>c</sup>	Yield (%) <sup>d</sup>
1 <sup>e</sup>		A	12	56	20
		B	4	99.2	46
		1	16	>99	43
2		A	6	63	23
		B	1.5	99.4	42
3		A	16	74	26
		B	10	99.6	43
4		A	12	53	21
		B	2	99.7	44
5		A	12	61	23
		B	3	99.4	42
6		A	12	47	19
		B	4	99.3	44
7 <sup>f</sup>		A	12	32	12
		B	6	99.4	45
8 <sup>g</sup>		A	48	28	10
		B	24	97.1	46

<sup>a</sup>The reaction were carried out 10.84 mmol scale by taking 0.55 equiv. H<sub>2</sub>O with respect to epoxide.<sup>b</sup>Catalyst loading based on racemic epoxides and for A =0.4 mol%; B=0.2 mol%. <sup>c</sup>% of ee was determined by chiral GC or chiral HPLC. <sup>d</sup>Isolated yield is based on racemic epoxides (theoretical maximum=50%). <sup>e</sup>For catalyst 1 reaction performed at 0-4°C with 0.5 mol% catalyst loading (Ref.8a). <sup>f</sup>Solvent THF: CH<sub>2</sub>Cl<sub>2</sub> 2:1 (v/v) with respect to epoxides. <sup>g</sup>THF is used as solvent.

encouraging than our previous report.<sup>11b,11c</sup> In order to check the stability of the dimeric catalyst **B** during HKR reaction, a control experiment was performed and treated with excess of water and

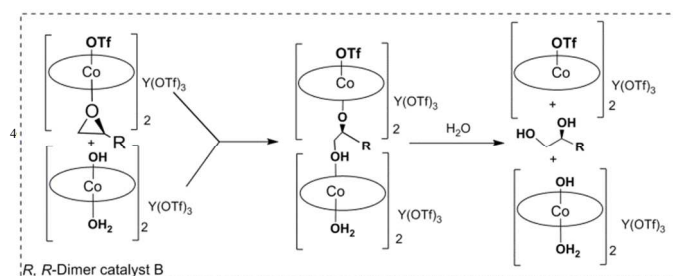
worked up and extracted by using  $\text{CH}_2\text{Cl}_2$  solvent, it showed the same reactivity and enantioselectivity in this HKR reaction. Additionally, the catalyst **B** can be regenerated and re-used at least up to three cycles without any appreciable loss in activity and enantioselectivity (see ESI Fig. S35).

These data indicates the catalyst **B** exhibits better stereochemical communication, optimal transition state geometry and possibly the cooperativity of Lewis acid  $\text{Y}(\text{OTf})_3$  assist to activate nucleophile which leads enhanced enantioselectivity.



**Fig.4** Kinetic study of the asymmetric HKR of the epichlorohydrin catalyzed by the monomer and dimer catalysts.

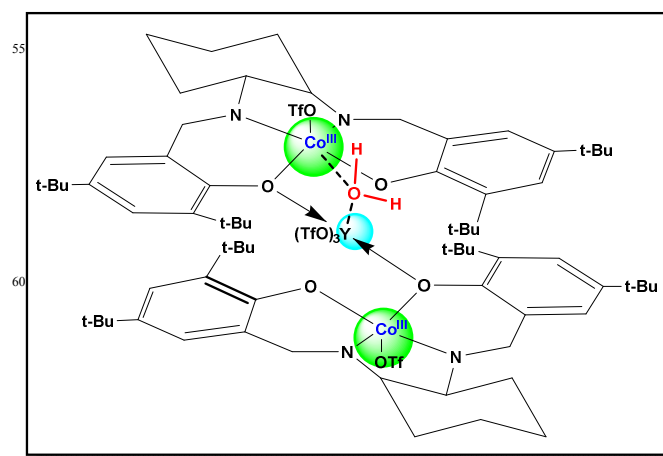
The HKR reaction catalyzed by dimeric catalyst **B** follows the cooperative bimetallic mechanism in a rate determining step where one salen Co unit acts as chiral Lewis acid centre which selectively binds with matched epoxides and another serving to deliver the hydroxide nucleophile. As proposed by the Jacobsen *et al.*,<sup>8b</sup> these interactions are mediated by the chiral, stepped conformations of the salen ligand (Scheme 1).



**Scheme I** Proposed mechanism for HKR of epoxides catalyzed by dimer salen Co catalyst B.

In the present HKR reaction, we propose that before forming  $\text{Co-OH}$  or  $\text{Co-OH}_2$  intermediate the  $\text{Y}(\text{OTf})_3$  support to activate the water molecule in order to bring close proximity towards salen Co centre and provides enhanced enantioselectivity in comparison to its monomer analogous (Scheme 2). The proposed mechanism shows complete agreement with the previously

reported yttrium triflate mediated asymmetric catalysis ring opening of aziridines,<sup>15</sup> and other asymmetric reaction.<sup>16</sup>



**Scheme 2:** Postulated structure for the activation of nucleophile mediated by  $\text{Y}(\text{OTf})_3$

In conclusion, the dimeric salen Co catalyst bearing  $\text{Y}(\text{OTf})_3$  shows high reactivity and enantioselectivity in the hydrolytic kinetic resolution with various terminal epoxides than its monomer analogous. Advantage of this new catalyst is its water tolerance property due to the reasonable moisture stability of  $\text{Y}(\text{OTf})_3$ . The role of different rare earth metal triflate with chiral metal complex in various asymmetric reactions is under progress in our laboratory.

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