

Urethanes. I. Organometallic Catalysis of the Reaction of Alcohols with Isocyanates*

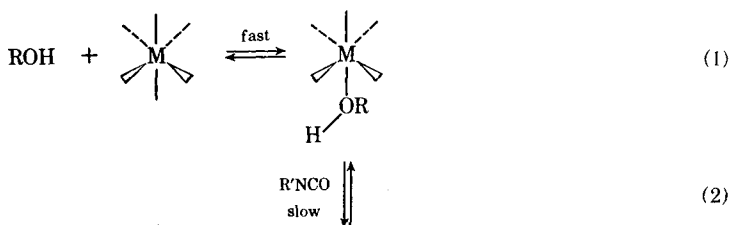
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Synopsis

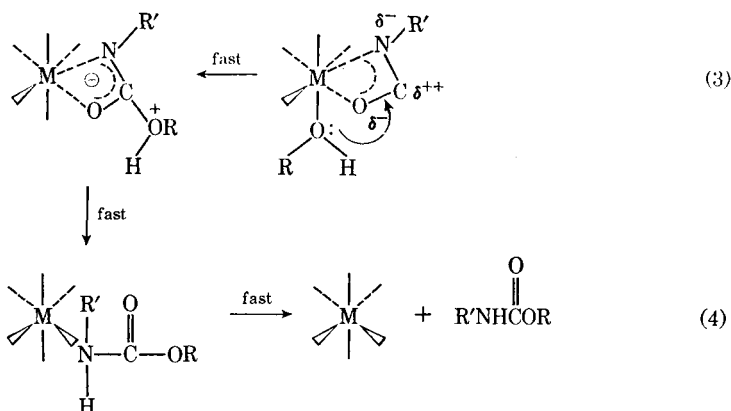
The catalysis of the reaction of *n*-butyl alcohol with isocyanates, using organometallic derivatives of lead, tin, and mercury, has been investigated. The rate of the reaction was measured by following the disappearance of the isocyanate absorption in the infrared. Phenyl, *n*-butyl, and cyclohexyl isocyanate were chosen to represent typical aromatic primary and secondary aliphatic isocyanates. Within the same series of catalysts, R_nMOAc , the catalytic effect decreases in the order $R_2Hg > R_3Sn > R_2Pb$; and in all cases $R = aryl > R = alkyl$. The electronic effects of substituents on the aryl moiety are not pronounced. Changes in X of R_nMX greatly affect the catalytic activity. The mechanism of organometallic catalysis of the alcohol-isocyanate reaction occurs via a template-type mechanism whereby the catalyst acts to complex both reactants in a catalyst phase allowing the reaction to occur with greater facility.

INTRODUCTION

The discovery of the excellent catalytic effect of organometallic compounds as well as of the metal carboxylates on the reaction of hydroxyl compounds with isocyanates has been of great significance for the synthesis of polyurethanes. Britain and Gemeinhardt¹ and Smith² have suggested that the metal carboxylates as well as organometallic species catalyze the isocyanate-alcohol reaction by formation of a ternary complex. Recently Robins³ has elaborated on this concept and suggested that the metal acts both to increase the electrophilic character of the isocyanate carbon through coordination with the isocyanate group in addition to bringing the reactants into close proximity, i.e., ternary complex (Scheme 1). Frisch

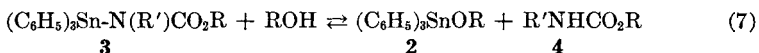
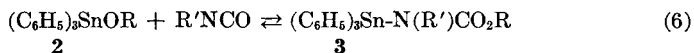
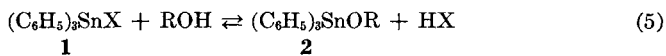


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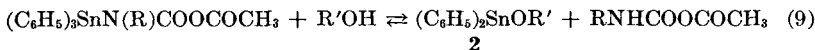
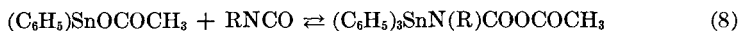
Scheme 1 shows the mechanism of metal catalysis via formation of a ternary complex.

and his co-workers⁴ have presented spectral evidence for a 1:1 complex of dibutyltin dilaurate with the hydroxyl component, as have Entelis et al.⁵ Davies and his co-workers, on the other hand, have observed that trialkyltin⁶ and trialkyllead⁷ alkoxides as well as phenylmercuric methoxide⁸ form 1:1 adducts with isocyanates which, except in the case of mercury, are reported to undergo rapid solvolysis. Thus, Bloodworth and Davies⁹ have suggested that the mechanism of catalysis of the alcohol-isocyanate reaction occurs via a series of substitution reactions (Scheme 2) for lead



Scheme 2 show the proposed mechanism of catalysis of alcohol-isocyanate reaction via substitution series

and tin catalysts in which the final solvolysis yields product 4 and catalyst 2, which can again proceed through the reaction sequence. A possible alternative mechanism leading to the reactive intermediate 2 is shown in Scheme 3. This mechanism has the interesting implication that the rate-



Scheme 3 Alternative route to reactive catalysts intermediate

determining step might be the slow conversion of the metal acetate to the metal alkoxide and that with suitable substituents a controlled delayed reaction would be anticipated. A similar mechanism may be operative in the catalysis of the isocyanate-hydroxyl reaction by tetraalkyldistannoxanes.¹⁰

In order to obtain useful information, we selected metals of known high catalytic activity, i.e., lead, tin, and mercury. The monoacetates were chosen as model compounds. Mercury compounds were included because of their reported activity.¹¹ Likewise aryl and alkyl substituents were compared, with the exception of mercury, where the alkyl acetate is not readily available. The model isocyanates selected for this study (phenyl, *n*-butyl, and cyclohexyl isocyanate) were chosen on the assumption that they best represent commercially available diisocyanates, such as MDI, HDI, and H₁₂MDI.

EXPERIMENTAL

Materials and Purification

Chloroform and tetrahydrofuran were distilled from *p*-toluenesulfonyl isocyanate before use in order to remove traces of moisture and ethanol. 1,4-Diazabicyclo-(2.2.2)octane (DABCO) (Matheson, Coleman and Bell) was sublimed before use. The isocyanates were distilled from phosphorus pentoxide before use: PhNCO, bp (8 mm) 54–55°; C₆H₁₁NCO, bp 167°; BuNCO, bp 113°. The following compounds were recrystallized before use: (C₆H₅)₃PbOAc, white feathers, chloroform, mp 204–206°; (C₆H₅)₃SnOAc, white plates, benzene, mp 124.5–125.5°; C₆H₅HgOAc, fluffy white needles, chloroform/benzene, mp 151–152°; Et₃PbOAc,* white needles, chloroform/benzene, mp 165–166°; Bu₃SnOAc, white needles, ether/hexane, mp 86.5–87°. The alcohols were distilled prior to use.

Procedure

Equipment. A water bath was maintained at the desired temperature for the kinetic studies. Aliquots were periodically removed for infrared analysis in a P&E Model 21. Nuclear magnetic resonance spectra were obtained on the Varian A-60, using TMS as an internal standard. Melting points are uncorrected and were taken on a Thomas-Hoover melting point apparatus.

Kinetic Procedure. Two stock solutions were made up in the solvent at 0.2*N* for the isocyanate and 0.2*N* or 2*N* for the alcohol at the bath temperature (30.6°) and stored in the bath. One 25-ml aliquot of each was mixed in a single-neck, round-bottomed 50-ml flask capped with a rubber septum. The catalyst was weighed out in a small glass vial which was immersed in the solution. The mixture was stirred and the first infrared scan taken ~3 min later. Dissolution of catalyst usually took less than 30 sec.

Reaction of Phenyl Isocyanate with Organometallic Acetates

In 50 ml of anhydrous chloroform, 5 mmoles each of catalyst and phenyl isocyanate were refluxed for 48 hr. In all experiments no changes occurred and the intensity of the phenyl isocyanate in the infrared remained constant, indicating that no adducts were being formed. Similarly when

* Skin irritation was very evident to F. W. Abbate when exposed to this compound.

2.2 ml of isocyanate and 25 ml benzene refluxed for 24 hr with catalyst present, no products were obtained.

Preparation of Mercury Esters

***p*-Chlorophenylmercuric Acetate.** Into 100 ml of chlorobenzene were placed mercuric oxide (red), 10.9 g (50 mmoles) acetic acid, 9 g (150 mmoles) and trifluoroacetic acid, 0.75 ml (~10 mmoles), and the mixture was refluxed overnight. The reaction mixture was cooled to room temperature and poured into ice water. Filtration of the white precipitate and drying in a vacuum oven yielded 10 g, 54% of a crude white solid, mp 160–175°. Recrystallization from methanol yielded either plates or needles, mp 189–190° (lit. 188–188.5°).¹²

***p*-Methoxyphenylmercuric Acetate.** A mixture of 100 ml of anisole, acetic acid (6 g, 100 mmoles), trifluoroacetic acid (1.14 g, 10 mmoles), and mercuric oxide (red) (10.9 g, 50 mmoles) was stirred at room temperature overnight. The mixture was poured into water, the anisole evaporated, and 14.1 g (77%) of crude white solid collected. Recrystallization from methanol raised the melting point to 179.5–181.5° (lit. 185–186°).¹³

Phenylmercuric Trifluoroacetate. Using the procedure of Hahn,¹⁴ 32.5 g (0.15 mole) of mercuric oxide (red) was slurried in 140 ml of dry benzene. To this was added at room temperature 34.2 g (0.30 mole) of trifluoroacetic acid. An immediate exothermic reaction took place. After 12 hr the benzene was reduced to a small volume and after addition of ligroin a white precipitate, 52.7 g (91%), mp 114–115°, was collected. Recrystallization* from benzene-petroleum ether (60–90°) yields two crystalline forms—needles, mp 115.5–116.5°, and cubes, mp 127–128°. These forms are readily interchangeable. Grinding or melting of the low-melting crystals results in the higher-melting form.

Phenylmercuric Neodecanoate. Phenylmercuric trifluoroacetate, 9.75 g (25 mmoles), and neodecanoic acid, 4.75 g (28 mmoles) (Enjay), bp 88° (0.25 mm), were dissolved in methanol and heated at 100° for one day on a Rotavap, under vacuum. An infrared scan of the liquid showed almost no acid present. The mixture was heated to 100° under low vacuum to remove the excess neodecanoic acid. The resulting thick yellowish oil had infrared and nuclear magnetic resonance spectra in line with the proposed structure.

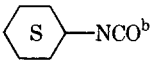
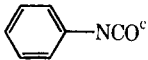
Phenylmercuric *n*-Butoxide. To phenylmercuric hydroxide, 2.9 g (10 mmoles), was added 5 ml of di-*n*-butylcarbonate and the ingredients were heated to 70–80° until gas evolution ceased. The excess carbonate was carefully removed via vacuum distillation and the residue was dissolved in benzene. Filtration and evaporation of the solvent yielded a clear liquid. The spectral data (ir and nmr) were consistent with the proposed structure. The compound was used without further purification.

* Recrystallization procedure of Hahn using alcohol-water mixtures results in slight decomposition, since phenylmercuric hydroxide is the first product collected during the crystallization procedure.

RESULTS AND DISCUSSION

In Table I the kinetic results obtained from the reaction of the model isocyanates and *n*-butanol in chloroform are shown. The order of catalytic activity of the metal acetates is Hg(II) > Sn(IV) > Pb(IV), and in the case of tin and lead the phenyl acetates are better catalysts than the alkyl acetates. This differentiation is not apparent from the results of Robins³

TABLE I
Isocyanate 1-Butanol Reaction^a

Catalyst	$-k, \text{min}^{-1} \times 10^3$		
	 -NCO ^b	<i>n</i> -C ₄ H ₉ NCO ^b	 -NCO ^c
None	0.064	0.147	0.575
C ₆ H ₅ COOH	0.544	1.11	8.33
1,4-Diazabicyclo- [2.2.2]octane	0.112	0.287	13.1
(C ₂ H ₅) ₃ PbOAc	0.595	1.68	13.2
(C ₆ H ₅) ₃ PbOAc	0.975	2.67	17.7
(<i>n</i> -C ₄ H ₉) ₃ SnOAc	2.05	3.46	23.0
(C ₆ H ₅) ₃ SnOAc	12.0	25.0	57.2
C ₆ H ₅ HgOAc	20.9	38.9	87.5

^a In CHCl₃, *T* = 30.6°; [NCO] = 0.1*N*.

^b [OH]/[NCO] = 10.

^c [OH]/[NCO] = 2.5.

Catalyst concentration = 5 mole-%; *k* is pseudo-first-order rate constant.

who applied a much less sensitive calorimetric method in his investigation of the catalytic activity of metal salts. However, this relative catalytic activity of lead and tin has also just been described by Davies¹⁵ who noted that if his proposed mechanism is operative (Scheme 2), the relative reactivity appears to be governed by the solvolysis stage, reaction (7). Since phenylmercuric carbamate is reported to be stable under the conditions of reaction (7),⁸ its high catalytic reactivity appears to be unexplainable by Davies' mechanism. The differences in relative rates are more pronounced in the reaction of the aliphatic isocyanates with *n*-butanol, and the rate increase for the slowest reacting, secondary isocyanate (C₆H₁₁NCO) over the noncatalyzed reaction is more than 300-fold for phenylmercuric acetate. It is also interesting to note that benzoic acid is not a bad catalyst as compared to triethylenediamine (DABCO). In fact, it is a better catalyst than DABCO in the reaction of an aliphatic isocyanate with *n*-butanol.

Secondly, the relative reactivity of the organometallic species used in the previous study as compared to some common catalysts used in polyurethane chemistry was measured. Mercury(II) acetate was also tested for its possible catalytic effect. The results are listed in Table II. Interest-

TABLE II
Catalysis by Metal Salts and Organometallics^a
 $C_6H_5NCO + n-C_4H_9OH \rightarrow C_6H_5NHCO_2C_4H_9-n$

Catalyst	$-k, \text{min}^{-1} \times 10^3$
$(C_6H_5)_3PbOAc$	17.7
$(n-C_4H_9)_3SnOAc$	23.0
Co(II) Octoate	31.3
Sn(II) Octoate	34.4
Hg(II) Acetate	40.2
$(C_6H_5)_3SnOAc$	57.2
C_6H_5HgOAc	87.5

^a In $CHCl_3$, $T = 30.6^\circ$; $[OH]/[NCO] = 2.5$; $[NCO] = 0.1N$. Catalyst concentration = 5 mole-%; k is pseudo-first-order rate constant.

ingly, the relative rates demonstrate that these salts are intermediate in reactivity between the triaryltin acetate and the trialkyltin acetate and that $Hg > Sn$ (although there exists some doubt as to whether tin(II) octoate would be more or less reactive than tin(II) acetate. Again, the high catalytic reactivity of mercury(II) acetate cannot be explained by the proposed mechanism of Davies.

In order to achieve further differentiation, several mercury compounds were synthesized and compared under identical conditions with the above metal acetates (Table III). Interestingly, substitution on the phenyl ring

TABLE III
Mercury Compounds as Catalysts^a
 $C_6H_5NCO + n-C_4H_9OH \rightarrow C_6H_5NHCO_2-C_4H_9-n$

Catalyst	$-k, \text{min}^{-1} \times 10^3$
None	0.575
C_6H_5HgCl	0.702
$C_6H_5HgOCOCF_3$	20.7
$C_6H_5Hg(\text{neoDec})$	20.8
$Hg(OBz)_2$	28.9
$Hg(OAc)_2$	40.2
$p\text{-MeOC}_6\text{H}_4\text{HgOAc}$	87.1
$p\text{-ClC}_6\text{H}_4\text{HgOAc}$	87.1
C_6H_5HgOAc	87.5

^a Identical conditions as in Table II.

gave little change in overall reaction rate; however, changes of the non-carbon substituent on the metal gave rise to substantial changes. The low reactivity of phenylmercuric chloride was also seen by Marchenko and Goldobin.¹¹ While the low catalytic activity of phenylmercuric neo-decanoate can be explained on steric grounds, the decrease of reactivity observed for phenylmercuric trifluoroacetate is most likely due to the difference in polarization of the metal to oxygen bond. For example, weaker bases such as chloride ion and trifluoroacetate ion markedly decrease the

catalytic effect, i.e., give rise to the formation of a more covalent bond. If the polarity of the metal to oxygen bond is further increased as, for example, in metal alkoxides, rapid reaction with the isocyanate occurs and a 1:1 adduct is formed via a 1,3-dipolar rearrangement. Apparently the metal acetates have an intermediate position, i.e., they are still coordinating with the isocyanate, but do not undergo the rearrangement necessary to form stable adducts. This fact is borne out by the observation that all investigated metal acetates can be refluxed in chloroform with equimolar amounts of phenyl isocyanate without noticeable change, or refluxed with phenyl isocyanate in benzene without any reaction occurring. If indeed adducts are formed by 1,3-rearrangement (which would indicate the intermediacy of the metal alkoxide in the catalytic scheme), further reaction with the isocyanate should give rise to the formation of the cyclic trimer, triphenyl isocyanurate. For example, from tributyltin methoxide and excess isocyanate, in the absence of a substrate, triisocyanurates are obtained.¹⁶

In an attempt to assess the effect of more than one ester grouping (dibutyltin diacetate is an excellent catalyst and an enormous amount of information with regard to its catalytic activity is known), we investigated the catalytic activity of phenyllead triacetate. Overmars and Van der Want¹⁷ have shown by gelation time measurements that phenyllead triacetate is a better catalyst than tributyllead acetate. The use of phenyllead triacetate in the system described in Tables I, II, and III gives rise to an extremely fast reaction, thus phenyllead triacetate is a catalyst for the alcohol-isocyanate reaction confirming Overmars and Van der Want's results.

Apparently substitution of ester linkage for the phenyl groups increases the acidity of the metal site to the point where the catalytic activity of lead surpasses that of mercury. Thus lead and tin have the advantage over mercury of increasing their acidity by substitution, whereas phenylmercury has reached its maximum by substitution of one. The catalytic activity of mercury(II) acetate is comparable to that of triphenyltin acetate but lower than that of phenylmercuric acetate (see Table II), thus clearly demonstrating the superiority of organomercuric esters over the metal esters. The advantage of a mercury catalyst may also depend on its planar configuration.

CONCLUSIONS

It appears that the proposed substitution mechanism of catalysis of the alcohol-isocyanate reaction suggested by Davies is not operative for the investigated organometallic esters and metal carboxylates. The high catalytic activity of phenylmercuric acetate and mercury(II) acetate coupled with the reported high stability to solvolysis of *N*-(phenylmercuric) carbamate⁸ and the suggestion by Davies that the overall catalysis depends on the solvolysis step (7)¹⁵ argue against this mode of catalysis, especially in the case of mercury(II) catalysis. Furthermore, a preliminary study in

tetrahydrofuran ($[\text{OH}]/[\text{NCO}] = 2.5$; $[\text{NCO}] = 0.1N$; $T = 30.6^\circ$; $[\text{CAT}] = 2$ mole-%) shows that not only is the rate of reaction using phenylmercuric *n*-butoxide as catalyst slower, by approximately one-half, than when phenylmercuric acetate is used, but also the rates are "zero order" in phenyl isocyanate for both mercury catalysts. Catalysis of the alcohol-isocyanate reaction, therefore, must be occurring by means of a template-type mechanism (Scheme 1), where coordination of the catalyst with one of the reactants, presumably the isocyanate, is highly unfavorable. The concentration of the reactive intermediate is therefore very small. The velocity of the reaction, depending on this catalyst complex containing both reactants, therefore becomes first order in the concentration of the complex and hence "zero order" is isocyanate.¹⁸

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