Michael addition of nitromethane to α,β-unsaturated carbonyl compounds over solid base catalysts

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Abstract

Michael additions of nitromethane to α,β-unsaturated carbonyl compounds (methyl crotonate, butene-2-one, 2-cyclohexene-1-one, and crotonaldehyde) were carried out at 273 K or 323 K over solid base catalysts such as alumina-supported potassium fluoride and hydroxide, alkaline earth oxides and lanthanum oxide. For all Michael additions of nitromethane, KF/alumina and KOH/alumina exhibited high activities, while MgO and CaO exhibited no activity for methyl crotonate and butene-2-one, but low activities for 2-cyclohexene-1-one and crotonaldehyde. The SrO, BaO, and La_2O_3 exhibited practically no activities for all Michael additions examined. The reactivity of each α,β-unsaturated carbonyl compound is discussed on the basis of the surface properties of catalyst and the chemical properties of the α,β-unsaturated carbonyl compound. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Michael addition is an addition of active methylene compounds to α,β-unsaturated carbonyl compounds. The mechanism for this reaction involves the formation of an anion from the active methylene compound, and the conjugate addition of the anion to the α,β-unsaturated carbonyl compound, followed by the acceptance of a proton. The reaction leads to form a new carbon–carbon bond under mild conditions. Therefore, it is useful in the synthesis of organic compounds of industrial interest.

Base-catalyzed Michael addition has been extensively studied in homogeneous systems [1,2]. So far, only a few attempts have been made over heterogeneous catalysts. An example of the heterogeneous catalyst is alumina-supported potassium fluoride (KF/alumina) over which Michael addition of nitroalkane to butene-2-one was undertaken [3–6]. Ando et al. reported that Michael addition of nitroalkane to butene-2-one proceeds very efficiently over KF/alumina at room temperature [4].

Although a series of alkaline earth oxides are representative solid bases and exhibit high activities for double bond isomerization of olefins [7–10], aldol condensation of acetone [11], and Tishchenko reaction of benzaldehyde [12], etc., their catalytic activities for Michael additions

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have not been reported except for self-Michael addition of methyl crotonate. We have recently studied the catalytic activity for self-Michael addition of methyl crotonate, and reported that only MgO exhibited a high activity [13].

A basic catalyst functions in abstraction of a proton from an active methylene compound to form an anion. It seems that the efficient basic catalyst for Michael addition may depend on the type of the active methylene compound and the α,β-unsaturated carbonyl compound. It is worthy to examine the catalytic activities of different types of solid bases for Michael additions of different active methylene compounds to different α,β-unsaturated carbonyl compounds.

In the present paper, we examine that Michael additions of nitromethane to methyl crotonate, butene-2-one, 2-cyclohexene-1-one, and crotonaldehyde over alumina-supported potassium fluoride and hydroxide, alkaline earth oxides, and lanthanum oxide. The reactivity of each α,β-unsaturated carbonyl compound is discussed on the basis of the surface properties of catalyst and the chemical properties of the α,β-unsaturated carbonyl compound.

2. Experimental

2.1. Catalysts

The types of solid base catalysts examined in the present study were alumina-supported potassium fluoride (KF/alumina) and hydroxide (KOH/alumina), a series of alkaline earth oxides, and lanthanum oxide.

KF/alumina was purchased from Fluka Chem., the KF content was 8.2 mmol/g, which was determined by XRF method. Alumina used for the catalyst and the support for KOH/alumina was supplied by the Catalysis Society of Japan (JRC-ALO4). KOH/alumina was prepared by impregnation of the alumina with an aqueous solution of KOH; the content of KOH was 3.6 mmol/g.

Magnesium oxide was prepared from commercial MgO (Merck) as follows. The MgO powder was soaked in distilled water. The slurry was stirred at room temperature for 24 h to form magnesium hydroxide, and dried at 373 K. Prior to the reaction, the magnesium hydroxide was decomposed to magnesium oxide in the reactor under a vacuum at an elevated temperature. Calcium oxide was prepared in the same way as MgO using calcium hydroxide (Kanto Chem.) as a starting material. Strontium oxide and barium oxide were prepared from $SrCO_3$ (Kanto Chem.) and $BaCO_3$ (Kanto Chem.), respectively, by outgassing at elevated temperatures.

Lanthanum oxide was prepared from $La(OH)_3$ by outgassing at an elevated temperature. The $La(OH)_3$ was prepared from an aqueous solution of $La(NO_3)_3$ by hydrolysis with an aqueous ammonia, followed by washing with distilled water and drying at 373 K.

2.2. Reaction procedures

Nitromethane, methyl crotonate, butene-2-one, 2-cyclohexene-1-one, and crotonaldehyde were purchased from Tokyo Kasei, and purified by passage through 4A molecular sieves to remove water and carbon dioxide exclusively from the reactants.

The reaction was carried out in an H-shaped glass batch reactor. The two branches of the reactor were separated by a breakable seal. The catalyst sample was placed in one branch, pretreated at an elevated temperature for 2 h in a vacuum, and sealed. The purified nitromethane and α,β-unsaturated carbonyl compound were degassed and stored in the other branch until they were introduced through the breakable seal by distillation into the branch containing the catalyst thermostated at liquid nitrogen temperature. Reaction was started by rapid melting of the reactant at a reaction temperature of 273 K or 323 K followed by stirring. After a certain reaction time, the products were separated from the catalyst by filtration and analyzed by GC with an OV-101 capillary column. For identification, the products were subjected to ^{1}H-NMR, MS, GC-MS, and elemental analysis.

2.3. MOPAC PRO calculation

The heats of formation of the reactants and products, and the charges on the carbon atoms of the α,β-unsaturated carbonyl compounds were calculated by use of MOPAC PRO delivered by CambrideSoft. In calculation, Hamiltonian potential function of AM1 (Austin Model 1) was used, and minimum RMA (Restrict Movement of selected Atoms) gradient was set to be 0.100.

3. Results and discussion

3.1. Reaction features

Reaction scheme of Michael addition of nitromethane to α,β-unsaturated carbonyl compounds is shown in Scheme 1. The α,β-unsaturated carbonyl compounds used in the present study were methyl crotonate, butene-2-one, 2-cyclohexene-1-one, and crotonaldehyde; these are ester, ketone, cyclic ketone, and aldehyde, respectively. The reaction is initiated by an abstraction of an H^+ from nitromethane by basic site on the catalyst to form nitromethanide anion as an intermediate. The produced nitromethanide anion attacks the carbon atom at β-position of α,β-unsaturated carbonyl compound to form the product anion. The product

Table 1
Heat of formation calculated by MOPAC PRO

| Compound	Reactant (kcal/mol)	Product[a] (kcal/mol)	Δ[b] (kcal/mol)
Nitromethane	−15.99		
Methyl crotonate	−80.66	−111.97	31.31
Butene-2-one	−24.05	−61.76	37.71
2-Cyclohexene-1-one	−34.67	−66.36	31.69
Crotonaldehyde	−27.00	−57.72	30.72

[a] Product is an addition of nitromethane to α,β-unsaturated carbonyl compound.
[b] Δ = Reactant − Product.
Hamiltonian potential function of AM1 was used.

anion picks up an H^+ from the catalyst surface to yield product.

The heats of formation calculated by MOPAC PRO for nitromethane, α,β-unsaturated carbonyl compounds and these products are listed in Table 1. The heat of formation for nitromethane is −15.99 kcal/mol. The heat of formation for all α,β-unsaturated carbonyl compounds are minus. The heats of formation of the reaction products are smaller than those of the corresponding α,β-unsaturated carbonyl compounds. These results lead to the conclusion that Michael addition of nitromethane to α,β-unsaturated carbonyl compounds is an exothermic reaction. Therefore, reaction products are more stable than the corresponding α,β-unsaturated carbonyl compounds. The heat of formation is the smallest for methyl crotonate than
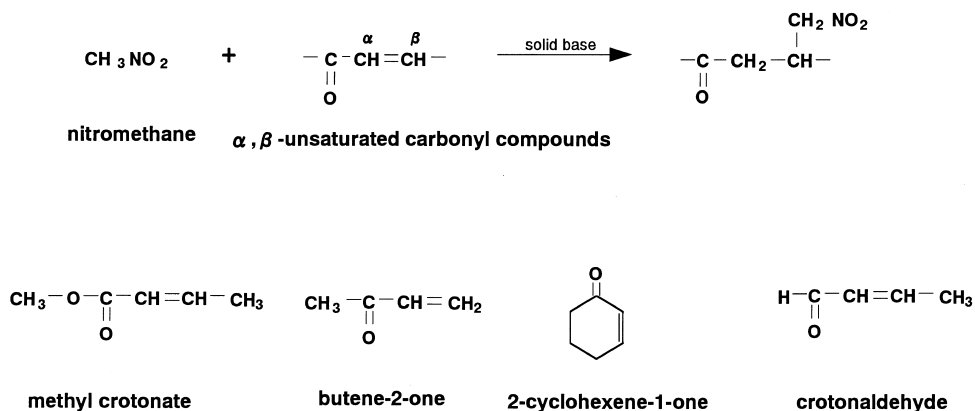
Scheme 1. Michael addition of nitromethane to α,β-unsaturated carbonyl compounds.

for any other α,β-unsaturated carbonyl compounds. On the other hand, the difference in the heat of formation (Δ) between reactant and product is the largest for butene-2-one among all of the Δs. Therefore, the reaction of nitromethane with butene-2-one is the most exothermic reaction among the reactions examined in the present study.

3.2. Catalytic activities of KF / alumina, KOH / alumina, MgO, and CaO

Table 2 presents the catalytic activities of KF/alumina, KOH/alumina, MgO, and CaO for Michael additions of nitromethane to α,β-unsaturated carbonyl compounds. These reactions were carried out under the conditions where molar content of nitromethane was three

or four times as much as that of α,β-unsaturated carbonyl compound. The products consisted exclusively of the compounds resulting from the attack of nitromethanide anion to β-position of α,β-unsaturated carbonyl compounds. The selectivities were higher than 99% for all the active catalysts. Conversion was calculated by decrease in the α,β-unsaturated carbonyl compound.

In Michael addition of nitromethane to methyl crotonate, KF/alumina and KOH/alumina exhibited high activity. MgO and CaO scarcely showed activity. The types of catalyst active for Michael addition of nitromethane to methyl crotonate are different from those for self-Michael addition of methyl crotonate for which only MgO is active [13]. However, self-Michael addition of methyl crotonate does not

Table 2
Catalytic activities for Michael addition of nitromethane to α,β-unsaturated carbonyl compounds over KF/alumina, KOH/alumina, MgO, and CaO

Catalyst	α,β-Unsaturated carbonyl compound	Pretreatment temperature (K)	Surface area (m^2 g^{-1})	Conversion[a] (%)
KF/alumina[b]	Methyl crotonate[d]	623	38	22.8[h,i]
KOH/alumina[b]	Methyl crotonate[d]	873	91	9.1[h,i]
MgO[b]	Methyl crotonate[d]	873	235	0.4[h,i]
CaO[b]	Methyl crotonate[d]	873	62	0.1[h,i]
KF/alumina[c]	Butene-2-one[e]	623	38	93.0[j,k]
KOH/alumina[c]	Butene-2-one[e]	873	91	49.0[j,k]
MgO[b]	Butene-2-one[e]	873	235	1.5[h,i]
CaO[b]	Butene-2-one[e]	873	62	0.9[h,i]
KF/alumina[b]	2-Cyclohexene-1-one[f]	623	38	99.8[h,k]
KOH/alumina[b]	2-Cyclohexene-1-one[f]	873	91	93.0[h,k]
MgO[b]	2-Cyclohexene-1-one[f]	873	235	20.5[h,k]
CaO[b]	2-Cyclohexene-1-one[f]	873	62	5.4[h,k]
KF/alumina[b]	Crotonaldehyde[g]	623	38	95.5[h,k]
KOH/alumina[b]	Crotonaldehyde[g]	873	91	95.8[h,k]
MgO[b]	Crotonaldehyde[g]	873	235	26.0[h,k]
CaO[b]	Crotonaldehyde[g]	873	62	16.6[h,k]

[a] Conversion was calculated by the decrease in α,β-unsaturated carbonyl compound.

[b] 100 mg.

[c] 10 mg.

[d] Nitromethane 12 mmol, methyl crotonate 4 mmol.

[e] Nitromethane 8 mmol, butene-2-one 2 mmol.

[f] Nitromethane 12 mmol, 2-cyclohexene-1-one 4 mmol.

[g] Nitromethane 12 mmol, crotonaldehyde 4 mmol.

[h] Reaction temperature, 323 K.

[i] Reaction time, 120 min.

[j] Reaction temperature, 273 K.

[k] Reaction time, 30 min.

proceed fast over MgO in the presence of nitromethane.

Butene-2-one undergoes Michael addition with nitromethane faster than methyl crotonate for all catalysts. The order of the catalytic activity was the same for both Michael additions: KF/alumina > KOH/alumina > MgO > CaO.

In Michael addition of nitromethane to 2-cyclohexene-1-one, KF/alumina and KOH/alumina exhibited a high activity. Also, MgO and CaO showed activity. The conversions were 20.5% and 5.4% for MgO and CaO, respectively.

In Michael addition of nitromethane to crotonaldehyde, the conversion of each of the catalysts was nearly the same as that observed in the reaction of 2-cyclohexene-1-one. MgO and CaO showed activity, the conversions being 26.6% and 16.6% for MgO and CaO, respectively.

The results given in Table 2 may be summarized as follows. (1) For methyl crotonate and butene-2-one, only KF/alumina and KOH/alumina were active, while for 2-cyclohexene-1-one and crotonaldehyde, not only KF/alumina

and KOH/alumina, but also MgO and CaO were active, where the former two catalysts being far more active than the latter two catalysts. (2) The order of the reactivities, regardless of the type of catalyst, was in the order: methyl crotonate < butene-2-one < 2-cyclohexene-1-one < crotonaldehyde.

3.3. Catalytic activity of other solid bases

Table 3 presents the catalytic activities for Michael additions of nitromethane to α,β-unsaturated carbonyl compounds over solid bases other than KF/alumina, KOH/alumina, MgO, and CaO. For Michael additions of nitromethane to methyl crotonate, butene-2-one, and 2-cyclohexene-1-one, γ-alumina and KF showed a considerable activity, though the activities were not high. It was observed in Section 3.2 that KF/alumina was most active among the four catalysts studied. In Michael addition of nitromethane to 2-cyclohexene-1-one, MgO and CaO were active (see Table 2), but SrO and BaO scarcely showed the activity.

Table 3
Catalytic activities for Michael addition of nitromethane to α,β-unsaturated carbonyl compounds over solid bases other than Table 2

Catalyst	α,β-Unsaturated carbonyl compound	Pretreatment temperature (K)	Surface area (m^2 g^{-1})	Conversion[a] (%)
γ-Alumina[b]	Methyl crotonate[d]	823	170	1.1[g,h]
SrO[b]	Methyl crotonate[d]	1073	10	0.2[g,h]
BaO[b]	Methyl crotonate[d]	1273	2	0.1[g,h]
La$_2$O$_3$[b]	Methyl crotonate[d]	873	33	0[g,h]
KF[c]	Butene-2-one[e]	373	0.4	3.0[i,j]
γ-Alumina[c]	Butene-2-one[e]	823	170	0.9[i,j]
KF[b]	2-Cyclohexene-1-one[f]	623	0.4	1.1[g,j]
γ-Alumina[b]	2-Cyclohexene-1-one[f]	823	170	6.9[g,j]
SrO[b]	2-Cyclohexene-1-one[f]	1073	10	1.4[g,j]
BaO[b]	2-Cyclohexene-1-one[f]	1273	2	0.7[g,j]
La$_2$O$_3$[b]	2-Cyclohexene-1-one[f]	873	33	0[g,j]

[a] Conversion was calculated by the decrease in α,β-unsaturated carbonyl compound.
[b] 100 mg.
[c] 10 mg.
[d] Nitromethane 12 mmol, methyl crotonate 4 mmol.
[e] Nitromethane 8 mmol, butene-2-one 2 mmol.
[f] Nitromethane 12 mmol, 2-cyclohexene-1-one 4 mmol.
[g] Reaction temperature, 323 K.
[h] Reaction time, 120 min.
[i] Reaction temperature, 273 K.
[j] Reaction time, 30 min.

Table 4
Charges calculated by MOPAC PRO

Compound	Carbonyl carbon	Carbonyl oxygen	α Position carbon	β Position carbon
Methyl crotonate	0.332	-0.360	-0.207	-0.070
Butene-2-one	0.252	-0.298	-0.248	-0.130
2-Cyclohexene-1-one	0.257	-0.293	-0.235	-0.093
Crotonaldehyde	0.211	-0.299	-0.278	-0.065

Hamiltonian potential function of AM1 was used.

Although La_2O_3 shows basic properties and catalyzes a number of base-catalyzed reactions [14], La_2O_3 was not active for Michael additions of nitromethane to methyl crotonate and 2-cyclohexene-1-one.

3.4. Catalytic activities and properties of alkaline earth oxides

For Michael additions of nitromethane to 2-cyclohexene-1-one and crotonaldehyde, MgO and CaO were active, as has been pointed out. The order of the activity for Michael additions of nitromethane to 2-cyclohexene-1-one and crotonaldehyde was in the order: MgO > CaO > SrO > BaO. The strength of basic site is in the order: MgO < CaO < SrO < BaO [11], while the surface area is in the order MgO > CaO > SrO > BaO. The activity is affected by both the strength of basic sites and the surface area. In the relations between the activity and properties of alkaline earth oxides, the activity and the surface area were in a similar trend. On the other hand, the activity and strength of basic site showed opposite trend. Although elucidation of definite active sites for the reaction is not possible at present, it is suggested that this reaction may not require strong basic sites.

3.5. Attempt to elucidation of reactivity by calculation of charge of α,β-unsaturated carbonyl compound

For Michael addition of nitromethane to α,β-unsaturated carbonyl compounds, the order of reactivity over KF/alumina, KOH/alumina, MgO and CaO was methyl crotonate < butene-2-one < 2-cyclohexene-1-one < crotonaldehyde. The reactivity order is assumed to be in the order of easiness of attack of nitromethanide anion to α,β-unsaturated carbonyl compounds. To confirm the assumption, the charges at the carbon atoms at β-position to carbonyl group were calculated by MOPAC PRO. The calculated results are given in Table 4. Michael addition can probably be illustrated by Scheme 2. The reaction proceeds via B to D intermediate. It is expected that α,β-unsaturated carbonyl compound reacts faster with nitromethanide anion as the charge at the β-position is more positive provided that the attack of nitromethanide anion is the slow step.

The order of the charge at the carbon atom at β-position is butene-2-one (-0.130) < 2-cyclohexene-1-one (-0.093) < methyl crotonate (-0.070) < crotonaldehyde (-0.065). The order is in accordance with the order of the
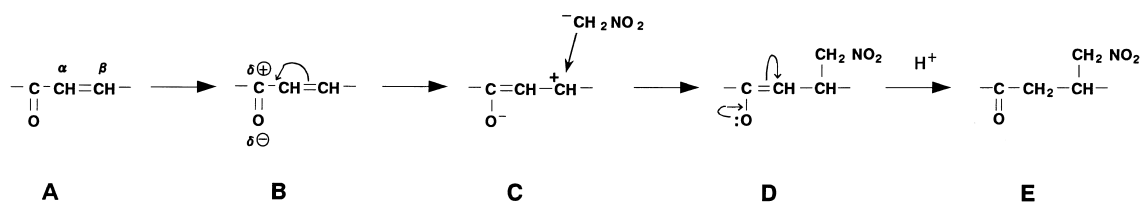
Scheme 2. Reaction mechanism for nitromethane anion attack to α,β-unsaturated carbonyl compound.

reactivity except for methyl crotonate which is least reactive. The reason why the reactivity of methyl crotonate is out of order is not clear yet, but can be explained by the difference in the slow step. The final protonation occurs at the α-position carbon atom of the anionic intermediate. The intermediate has two oxygen atoms which withdraw electron near the α carbon. The α carbon then loses the reactivity toward proton, which results in the slow step being the protonation at the α-carbon. An alternative explanation may be as follows. The product has two oxygen atoms, and interacts strongly with the catalyst surface. As a result, the desorption of the product becomes slow.

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