DOI: 10.1002/adsc.200600305

Activation of C−Cl Bonds in Chloroalkanes by Nickel Oxide Nanoparticles: Formation of Tetrasubstituted Ammonium Salts from Tertiary Amines

Kang Hyun Park,[a] Il Gu Jung,[a] Young Keun Chung,[a,]* and Jin Wook Han[b,]*

[a] Intelligent Textile System Research Center, and Department of Chemistry, College of Natural Sciences, Seoul National University, Seoul 151-747, Korea
[b] Department of Chemistry, Hanyang University, Seoul 133-791, Korea
Fax: (+82)-2-2299-0762; e-mail: jwhan@hanyang.ac.kr

Received: June 26, 2006

Supporting information for this article is available on the WWW under http://asc.wiley-vch.de/home/.

Abstract: Nickel oxide nanoparticles, readily available and easy to handle, were found to be an effective catalyst in the catalytic activation of C−Cl bonds in chloroalkanes. Coupling reactions of chloroalkanes and tertiary amines in the presence of the nickel oxide nanoparticle catalyst gave moderate to high yields of quaternary ammonium salts depending upon the amines.

Keywords: amination; ammonium salts; C−Cl bond activation; heterogeneous catalysis; nanoparticles; nickel oxide

Introduction

Activation of halogen-substituted alkanes has been extensively studied because of the interest in the destruction and conversion of chlorine-containing hydrochlorofluorocarbon (HCFC) analogues[1] and in various organic transformation processes catalyzed by transition metal complexes.[2] The activation of C−X bonds by chemical methods essentially involves reactions at a metal surface[3] or oxidative addition at the metal center of complexes.[4] Of particular interest is the activation of the relatively inert C−Cl bond. The majority of dihalomethane activation reactions include only a handful of examples with CH_2Cl_2. The reaction of tertiary amines with dihalomethanes at high pressures yielded quaternary halomethylammonium salts.[5] The conversion of tertiary amines with alkyl halides to quaternary ammonium salts is called the Menshutkin reaction.[6] Because of the importance of alkyl transfers in biochemical processes,[7] the Menshutkin reaction has been the subject of extensive experimental and theoretical studies.[8] However, its use in organic synthesis has been quite limited.[9]

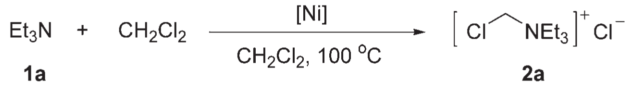
We herein report the C−Cl bond activation of chloroalkanes in the presence of nickel oxide catalysts. To the best of our knowledge, this is the first general, simple, and efficient method for activating the C−Cl bonds of chloroalkanes. Furthermore, the nickel oxides used as catalysts in the reaction are ubiquitous, commercially available and easy to handle.

Results and Discussion

During our studies on the nickel-catalyzed cycloaddition reaction of alkynes in the presence of triethylamine in dichloromethane solution, we found that instead of a cycloaddition reaction of alkynes, C−Cl bond activation in dichloromethane occurred to give (chloromethyl)triethylammonium chloride (**2a**) by the coupling of dichloromethane with triethylamine (**1a**). This unexpected observation prompted us to investigate the C−Cl bond activation of chloroalkanes in the presence of nickel catalysts in detail.

Nickel catalysts were examined for their catalytic activity and reusability in the activation of the C−Cl bond in dichloromethane and its coupling with triethylamine (Table 1). Because we focused on the reusability and ready availability of catalysts, including stability to air oxidation as well as catalytic activity, Raney nickel and nickel oxides were the first choice for nickel catalysts that could be easily recovered and reused without losing catalytic activity. The C−Cl activation and coupling reaction of dichloromethane and **1a** was carried out in the presence of 5 mol% of the appropriate nickel catalysts at 100 °C in a sealed tube. The resulting **2a** was purified by filtration followed by

Table 1. C−Cl bond activation of CH_2Cl_2 and coupling with Et_3N in the presence of Ni catalysts.



Entry	Catalyst	Reaction Time [h]	Yield [%][a]
1	Raney Nickel[b]	12	27
2	Raney Nickel[c]	12	94
3	Recovered from # 2	12	68
4	Bulk NiO[d]	12	81
5	Recovered from # 4	12	83
6	NiO nanoparticles[e]	12	99
7	Recovered from # 6	10	99
8	Recovered from # 7	10	99
9	Recovered from # 8	10	99
10	Recovered from # 9	10	99
11	None	20	-

[a] Isolated yields based on triethylamine used.
[b] An aged sample of Raney nickel.
[c] A freshly opened sample of Raney nickel.
[d] Bulk NiO (~325 mesh, commercially available).
[e] NiO nanoparticle (10-20 nm, commercially available).

recrystallization from dichloromethane and diethyl ether. The formation of **2a** was confirmed by combustion analysis, ^{1}H NMR, and an X-ray diffraction study (Figure 1). The salt **2a** had been previously synthesized by the reaction of Et_3N with CH_2Cl_2 under high pressure (10 kbar).[10] Double C−Cl activation of dichloromethane and coupling with two triethylamine molecules which would give the *N,N,N,N′,N′,N′*-hexaethylmethanediammonium salt was not observed in the present reaction conditions at all. The results with various nickel sources are summarized in Table 1.

As shown in Table 1, Raney nickel and nickel oxides with various sizes, which are commercially available, were screened in this reaction as catalysts. In the case of Raney nickel catalysts, the freshness of catalyst would be an important factor to show a catalytic activity for this C-Cl activation and coupling reaction (entries 1–3 in Table 1). A high yield of **2a** was observed in the presence of fresh Raney nickel which was opened just before the reaction (entry 2). However, reuse of the recovered Raney nickel and use of an aged sample as a catalyst showed inferior activity to the fresh one under the same reaction conditions (entries 1 and 3). Thus, an aged and the recovered Raney nickel catalyst gave 27 % and 68 % yields of **2a**, respectively. The freshness of the Raney nickel is critical to the reaction. In spite of the fact that Raney nickel has shown catalytic activity in C−Cl activation and coupling of dichloromethane with **1a**, it does not seem to be a good choice of catalyst with regard to its reusability.

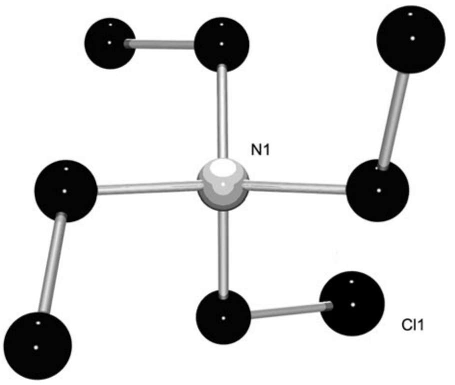
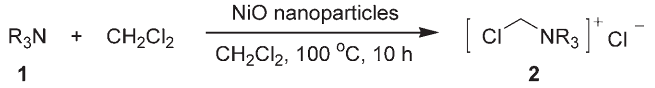
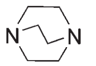
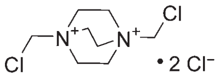


Figure 1. Ball-and-stick representation of $[Et_3NCH_2Cl]^+Cl^-$.

On the other hand, the ready availability of nickel oxide and its use in combination with other metal oxides in hydrodechlorination reactions encouraged us to examine the use of nickel oxides as catalysts in the C−Cl activation and coupling of dichloromethane with **1a**. Effects of the size of nickel oxide catalysts on the catalytic activity were examined in this coupling reaction. It was found that a nano-sized NiO catalyst, which is commercially available, gave an excellent yield of **2a** and was also reused without loss of any catalytic activity in the reaction (entries 6–10). Thus, the reaction of dichloromethane with **1a** in the presence of nickel oxide nanoparticles having a small size of 10–20 nm, which were purchased from Aldrich, gave a quantitative yield of **2a** (entry 6). Quantitative yields of **2a** were also observed with the recovered NiO nanoparticle catalyst (entries 7–10). The catalyst maintained its excellent catalytic activity for the reaction even after being cycled five times. A maximum reusability of the catalyst has not been tested yet. Bulk nickel oxide having a size of 44 μm (325 mesh), which is also commercially available, was examined as a catalyst in the reaction for comparison (entries 4 and 5). With bulk NiO catalysts we observed an 81 % yield of **2a** under the same reaction conditions as for the nano-sized NiO catalysts (entry 4). Owing to the increased surface area of nano-sized catalysts in the heterogeneous reaction, nickel oxide nanoparticles could show a better catalytic activity than bulk nickel oxide. Notably, an 83 % yield of **2a** was observed with the recovered bulk NiO catalyst, showing that it had not lost its catalytic activity in reuse just like the NiO nanoparticles (entry 5). The high reusability of NiO catalysts could be attributed to the inherent stability of metal oxides and the absence of leaching into the reaction media. Elemental analysis (by ICP-AES) of the reaction mixture after completion of the reaction revealed that less than 0.1 ppm of nickel had been leached out into the solution. Moreover, elemental composition analysis by an SEM/EDS experiment with the NiO nanoparticles after a catalytic reaction revealed that the molar ratio of Ni and O atoms was about 1:1. There were no significant composition

Table 2. Catalytic C–Cl bond activation of CH_2Cl_2 and coupling with various tertiary amines in the presence of NiO nanoparticles.[a]



Entry	Amine (1)		Product(s) (2)		Yield [%][b]
1	NEt_3	**1a**	$[ClCH_2NEt_3]^+Cl^-$	**2a**	99
2	NBu_3	**1b**	$[ClCH_2NBu_3]^+Cl^-$	**2b**	99
3	EtN(*i*-Pr)$_2$	**1c**	$[ClCH_2NEt(iPr)_2]^+Cl^-$	**2c**	0
4	$Me_2NCH_2NMe_2$	**1d**	$[(ClCH_2)Me_2NCH_2NMe_2(CH_2Cl)]^{2+} \cdot 2\ Cl^-$	**2d**	25
5		**1e**		**2e**	99
6	NC_5H_5	**1f**	$[ClCH_2NC_5H_5]^+Cl^-/[C_5H_5NCH_2NC_5H_5]^{2+} \cdot 2\,Cl^-$	**2f/2g**	42/38

[a] *Reaction conditions:* an amine (**1**, 2.87 mmol), CH_2Cl_2 (1 mL, 15.6 mmol), NiO nanoparticles (5 mol%), 100 °C, and 10 h.
[b] Isolated yields based on amines used.

change of the NiO nanoparticles during the catalytic reaction (see Supporting Information). As expected, in the absence of a metal species, no reaction was observed (entry 11). Nickel oxide nanoparticles, readily available, were the catalyst of choice in the sense that they showed excellent catalytic activity and reusability in the catalytic C–Cl bond activation of dichloromethane and coupling with triethylamine.

The scope of tertiary amines was also investigated in the C–Cl bond activation of CH_2Cl_2 and coupling with tertiary amines in the presence of NiO nanoparticles (Table 2). Steric and electronic factors of the substituents on the amines played important roles in the catalytic activity. In the case of primary alkyl substituents on the amine, quantitative yields for **1a** and tributylamine (**1b**) were observed under the present reaction conditions to give **2a** and (chloromethyl)tributylammonium chloride (**2b**), respectively, while the reaction with *N,N*-diisopropylethylamine (**1c**) did not give the corresponding quaternary ammonium salt (**2c**) at all (entries 1–3). Tertiary diaminoalkanes were also examined for the C–Cl bond activation of dichloromethane and coupling under NiO nanoparticle catalysts (entries 4 and 5). The reaction of CH_2Cl_2 with *N,N,N′,N′*-tetramethyldiaminomethane (**1d**) and 1,4-diazabicyclo[2.2.2]octane (**1e**) gave 25% and 99% isolated yields of the corresponding diammonium salts (**2d** and **2e**), respectively. Both N atoms in a diamine were coupled with the activated C–Cl bond of CH_2Cl_2 to make two C–N bonds in the product molecule. Especially, a part of the double activation of both C–Cl bonds in a dichloromethane molecule was observed in the catalytic reaction of pyridine (**1f**) and CH_2Cl_2 under the same reaction conditions (entry 6). Thus, the reaction of **1f** and CH_2Cl_2 in the presence of NiO nanoparticles as a catalyst at 100 °C for 10 h gave a mixture of a singly activated product **2f** and a doubly activated product **2g** in 42 and 38% yields, respectively. Although multiple C–Cl activations of dihaloalkanes have been previously reported with bimetallic nanoparticles,[11] this activation of both C–Cl bonds in dichloromethane with nickel oxide nanoparticles is the first example to the best of our knowledge. Unfortunately, no reaction was observed for tertiary amines having more than one aryl substituent. Triphenylamine and *N,N*-dimethylaniline were tested in the coupling with dichloromethane under NiO nanoparticle catalysts, but in vain. The starting tertiary arylamines were recovered quantitatively after the reaction period. It seems that the reaction may be highly dependent upon the steric and electronic effects of the substituents in an amine. Recently, ionic liquids have attracted a lot of attention owing to their uses as a green solvent, a soluble support, a catalyst, and so on [12]. The quaternary ammonium salts, synthesized in entries 2 and 3 of Table 2, have low melting points and can be considered as ionic liquids at room temperature.

Next, the scope of the haloalkanes was investigated in the C–Cl bond activation of various haloalkanes and coupling with triethylamine in the presence of NiO nanoparticles (Table 3). To evaluate the extent of simple nucleophilic substitution reactions between triethylamine and chloroalkanes, control experiments for the chloroalkanes in Table 3 under the same reaction conditions were carried out in the absence of NiO nanoparticles. As mentioned earlier for entry 11 of Table 1, the reaction between dichloromethane and triethylamine did not give any product without a catalyst even after a prolonged reaction time. However, a nucleophilic substitution reaction between triethylamine and the other chloroalkanes without an NiO catalyst did occur to give the corresponding quaternary ammonium products to some extent. Thus, the nucleophilic substitution reactions of allyl chloride (**3a**), benzyl chloride (**3b**), 1,2-dichloroethane (**3c**), 1,3-

Table 3. Catalytic C–Cl bond activation of various chloroalkanes and coupling with Et_3N in the presence of NiO nanoparticles.[a]

$$Et_3N + \underset{\mathbf{3}}{R\text{-}Cl} \xrightarrow[100\ ^{o}C,\ 10\ h]{\text{NiO nanoparticles}} \underset{\mathbf{4}}{[R\text{-}NEt_3]^+Cl^-}$$

Entry	Chloroalkane (**3**)		Product (**4**)		Yield [%][b]
1	$H_2C{=}CHCH_2Cl$	**3a**	$[H_2C{=}CHCH_2NEt_3]^+Cl^-$	**4a**	90
2	$PhCH_2Cl$	**3b**	$[PhCH_2NEt_3]^+Cl^-$	**4b**	70
3	$ClCH_2CH_2Cl$	**3c**	$[ClCH_2CH_2NEt_3]^+Cl^-$	**4c**	70
4	$ClCH_2CH_2CH_2Cl$	**3d**	$[ClCH_2CH_2CH_2NEt_3]^+Cl^-$	**4d**	44
5	$ClCH_2CH_2CH_2CH_2Cl$	**3e**	$[ClCH_2CH_2CH_2CH_2Net_3]^+Cl^-$	**4e**	38
6	$NCCH_2CH_2Cl$	**3f**	$[NCCH_2CH_2NEt_3]^+Cl^-$	**4f**	99
7	$MeOCH_2CH_2Cl$	**3g**	$[MeOCH_2CH_2NEt_3]^+Cl^-$	**4g**	19

[a] *Reaction conditions:* triethylamine (**1a**, 2.87 mmol), chloroalkanes (**3**, 15.6 mmol), NiO nanoparticles (8 mg), 100 °C, and 10 h.

[b] Isolated yields based on triethylamine used.

dichcloropropane (**3d**), and 1,4-dichlorobutane (**3e**) with triethylamine gave the corresponding quaternary ammonium products in 45, 54, 3, 5, and 5 % yields, respectively. With these control experimental data in hand, the C–Cl bond activation of various haloalkanes and coupling with triethylamine under NiO nanoparticle catalysts were examined carefully. All the chloroalkanes in Table 3 showed higher yields of the desired products in the presence of catalyst than in the absence of catalyst. For example, the yield for **3c** was dramatically enhanced from 3 % to 77 % by adding NiO nanoparticle catalysts (entry 3). This implies that the catalytic C–Cl activation and coupling, rather than nucleophilic substitution, is the major pathway for the formation of quaternary ammonium salts from the reaction of tertiary amine and chloroalkanes. Double C–Cl activation of dichloroalkanes and coupling with two triethylamine molecules that would give the corresponding diammonium salt was not observed in the present reaction conditions at all. The chloroalkylated quaternary ammonium product, such as **4c**, **4d**, and **4e**, is a useful organic intermediate that can be further derivatized utilizing the remaining C–Cl moiety. The catalytic activity is relatively sensitive to the electronic characteristics of a substituent of chloroalkanes (entries 3, 6, and 7). While only a 19 % yield of **4g** was obtained for 1-chloro-2-methoxyethane (**3g**) that had an electron-donating methoxy group, 77 % and 99 % yields of **4c** and **4f** were obtained for 1,2-dichloroethane (**3c**) and 1-chloro-2-cyanoethane (**3f**) that had an electron-withdrawing group, respectively. It is deduced from the results that the NiO-catalyzed C–Cl activation and coupling is facilitated by electron-deficient chloroalkanes, rather than electron-rich chloroalkanes. However, unlike chloroalkanes, haloarenes, such as chlorobenzene and bromobenzene, exhibited no activity in the present conditions, which implied that the transition metal-catalyzed cross-coupling, consisted of oxidative addition and reductive elimination as main catalytic steps, might not be operational in the present catalytic cycles. Moreover, any β-hydride elimination product, which is a main side product in conventional transition metal-catalyzed cross-coupling reactions of haloalkanes,[13] was not detected in the reactions at all. At this moment, it is very difficult to characterize the exact reaction mechanism of NiO nanoparticle-catalyzed C–Cl bond activation of chloroalkanes and coupling with amines.

We next examined the kinetics on the reaction of dichloromethane and triethylamine. The reaction conditions were as follows, 0.1 mol % NiO and Figure 2 shows the plot of reaction time versus yield and TOF.

The high catalytic activity of the nano-sized NiO catalyst in this transformation is clearly demonstrated by the kinetic profile and TOF value of the reaction of triethylamine and dichloromethane in the presence of 0.1 mol % of NiO nanoparticles as shown in Figure 2. Even though the catalyst loading was reduced from 5 mol % to 0.1 mol %, the reaction was

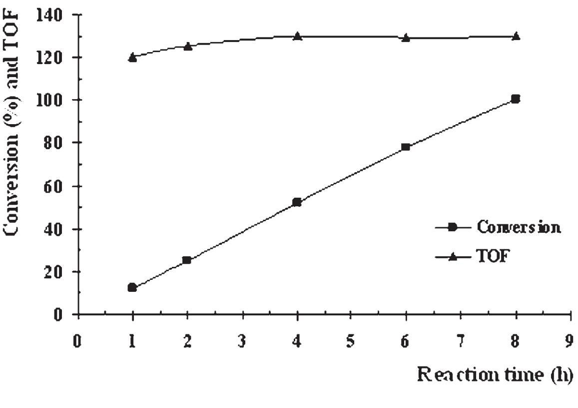


Figure 2. Kinetic profile and TOF value.

completed within 8 h. According to the kinetic profile, the turnover frequency (TOF) of the reaction was around 125 h^{-1} all through the conversion.

Conclusions

In conclusion, we have demonstrated the first general and facile C–Cl bond activation of chloroalkanes including dichloromethane and coupling with various tertiary amines to give quaternary ammonium salts catalyzed by nickel oxide nanoparticles. The nickel oxide nanoaprticles were easily recovered and can be reused at least five times without any loss of catalytic activity. The reaction provides a useful and problem-free synthetic route to ionic liquids with diverse substituents without any difficulty and represents a variation of the Menshutkin reaction. Current efforts in our laboratory are directed towards a deeper understanding of the mechanism and synthetic applications of this new type of reaction.

Experimental Section

General Information

Solvents were dried and distilled according to standard methods before use. Dichloromethane was distilled form P_2O_5 under nitrogen. Reagents were purchased from Aldrich Chemical Co. and Strem Chemical Co. and were used as received. All yields are based upon isolated material. ^{1}H NMR and ^{13}C NMR spectra were obtained with a Bruker 300 MHz spectrometer. Coupling constants (J values) are reported in Hertz (Hz), and spin multiplicities are indicated by the following symbols: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet). Elemental analyses were done at the National Center for Inter-University Research Facilities, Seoul National University. High Resolution Mass Spectra were obtained at Korea Basic Science Institute (Daegu, Korea). High-resolution mass spectrometry (HR-MS) data are reported in the form of *m/z* (intensity relative to base peak = 100). Diffraction data of (chloromethyl)triethyl ammonium chloride (**2a**, $[Et_3NCH_2Cl]^+Cl^-$) for structure determination were measured with an Enraf–Nonius CCD single-crystal X-ray diffractometer at room temperature using graphite-monochromated Mo Kα radiation ($\lambda = 0.71013$ Å). Preliminary orientation matrixes and unit cell parameters were obtained from the peaks of the first 10 frames and then refined using the whole data set. Frames were integrated and corrected for Lorentz and polarization effects using DENZO. The structure was solved by direct methods using SHELXS-97 and refined by full-matrix least-squares fitting with SHELXL-97. All non-hydrogen atoms were refined anisotropically, and all hydrogen atoms not involving hydrogen bonding were treated as idealized contributions.

Catalytic Testing

To a solution of a tertiary amine (2.87 mmol) in 1 mL of CH_2Cl_2 (15.6 mmol) was added nickel oxide nanoparticles (5 mol%) or Raney nickel (5 mol%), and the reaction mixture was stirred at 100 °C for 10 h. A white precipitates appeared as the reaction went on. After the reaction the mixture was allowed to cool to room temperature, followed by filtration to obtain the chloromethylated quaternary ammonium salts. Nickel oxide or Raney nickel catalyst was recovered from the product by centrifuge. The recovered nickel catalyst was reused for the further catalytic reactions.

Characterization by X-Ray Crystallography

Crystal data for (chloromethyl)triethylammonium chloride (**2a**): $M = 204.13$, monoclinic, space group $P2_1/n$, $a = 11.26(5)$, $b = 8.060(5)$, $c = 12.515(5)$ Å, $\beta = 106.527(5)^o$, $V = 1088.5(9)$ Å^3, $T = 293(2)$ K, $Z = 4$, $\mu = 0.551$ mm^{-1}, $\rho_{cald} = 1.246$ mg m^{-3}, $F(000) = 440$, no. of data collected: 4229, no. of unique data: 2465, $R = 0.0678$, $Rw = 0.1937$. Crystallographic data for **2a** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number of CCDC 247262. These data can be obtained free charge via www.ddcd.cam.ac.uk/consts/retrieving.html [or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB21EZ, UK; fax: (+44)1223–336–033; or deposit@ddcd.cam.ac.uk].

Characterization of New Compounds

$[C_8H_{19}NCl]^+Cl^-$ (4c): ^{1}H NMR ($CDCl_3$): $\delta = 3.81$ (t, $J = 6.6$ Hz, 1H), 3.53 (t, $J = 6.3$ Hz, 1H), 2.81 (q, $J = 7.2$ Hz, 6H), 1.08 (t, $J = 7.2$ Hz, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz): $\delta = 54.3$, 46.3, 36.4, 9.1; HR-MS: $m/z = 164.1201$, calcd. for $C_8H_{19}N_1Cl_1$: 164.1206; anal. calcd. for $C_8H_{19}NCl$: C 58.49, H 11.67, N 8.53; found: C 58.65, H 11.66, N 8.92.

$[C_9H_{21}NCl]^+Cl^-$ (4d): ^{1}H NMR ($CDCl_3$): $\delta = 3.68$ (br, 2H), 3.64 (br, 1H), 3.23 (br, 6H), 3.11 (br, 1H), 2.38 (br, 2H), 1.44 (br, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz): $\delta = 57.7$, 49.1, 46.6, 21.1, 9.7; HR-MS: $m/z = 178.1369$, calcd. for $C_9H_{21}NCl$: 178.1363; anal. calcd. for $C_9H_{21}N_1Cl$: C 60.63, H 11.88, N 7.86; found: C 60.45, H 11.53, N 8.11.

$[C_{10}H_{23}NCl]^+Cl^-$ (4e): ^{1}H NMR ($CDCl_3$): $\delta = 3.91$ (br, 2H), 3.62 (br, 6H), 3.17 (br, 2H), 2.48 (br, 2H), 1.53 (br, 9H), 1.26 (br, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz): $\delta = 55.7$, 54.2, 46.7, 43.9, 26.0, 9.3; HR-MS: $m/z = 192.1519$, calcd. for $C_{10}H_{23}NCl$: 192.1519; anal. calcd. for $C_{10}H_{23}NCl$: C 62.45, H 12.06, N 7.29; found: C 62.55, H 12.23, N 7.38.

Acknowledgements

This work was supported by grant No. (R01–2005–000–10548–0) from the Basic Research Program of the Korea Science & Engineering Foundation. J. W. H. is grateful to the research fund of Hanyang University (HY-2003).

References

[1] a) A. Wiersma, E. J. A. X. van de Sant, M. Makkee, H. van Bekkum, J. A. Moulijn, *Stud. Surf. Sci. Catal.* **1996**, *101*, 369; b) L. E. Manzer, V. N. M. Rao, *Adv. Catal.* **1993**, *39*, 329.

[2] a) V. V. Grushin, H. Alper, *Chem. Rev.* **1994**, *94*, 1047; b) S.-I. Iwamatsu, H. Kondo, K. Matsubara, H. Nagashima, *Tetrahedron* **1999**, *55*, 1687.

[3] a) G. Zhou, A. J. Gellman, *J. Catal.* **2002**, *194*, 233; b) S. C. York, D. F. Cox, *J. Phys. Chem. B* **2003**, *107*, 5182.

[4] a) R. Dorta, L. J. W. Shimon, H. Rozenberg, D. Milstein, *Eur. J. Inorg. Chem.* **2002**, 1827; b) A. Aballay, F. Godoy, G. E. Buono-Core, A. H. Klahn, B. Oelckers, M. T. Garland, J. C. Munoz, *J. Organomet. Chem.* **2003**, *688*, 168; c) H. F. Haarman, J. M. Ernsting, M. Kranenburg, H. Kooijman, N. Veldman, A. L. Spek, P. W. N. M. van Leeuwen, K. Vrieze, Organometallics **1997**, *16*, 887.

[5] B. Almarzoqi, A. V. George, N. S. Isaacs, *Tetrahedron* **1986**, *42*, 601.

[6] For a review of the Menshutkin reaction, see: J.-L. M. Abboud, R. Notario, J. Betran, M. Sola, *Prog. Phys. Org. Chem.* **1993**, *19*, 1.

[7] L. Stryer, *Biochemistry*, 4th edn., Freeman, New York, **1995**, pp. 328, 722, and 998.

[8] a) L. M. V. Pinheiro, A. R. T. Calado, J. C. R. Reis, Org. Biomol. Chem. **2004**, *2*, 1330; b) E. Owczarek, W. Kwiatkowski, M. Lemieszewski, A. Mazur, M. Rostkowski, P. Paneth, *J. Org. Chem.* **2003**, *68*, 8232; c) H. Hirao, Y. Nagae, M. Nagaoka, *Chem. Phys. Lett.* **2001**, *348*, 350; d) H. Castejon, K. B. Wiberg, *J. Am. Chem. Soc.* **1999**, *121*, 2139.

[9] a) M. Nanasawa, N. Kosaki, T. Kaneeko, M. Hirai, *Heterocycl. Commun.* **2003**, *9*, 57; b) H. Nishida, T. Fujii, Y. Abiru, K. Yatsuki, M. Yamamoto, N. Shimizu, K. Kakemi, M. Mikawa, M. Kise, *Bull. Chem. Soc., Jpn.* **1994**, *67*, 1419; c) C. Lim, S.-Y. Kim, S.-D. Yoh, M. Fujio, Y. Tsuno, *Tetrahedron Lett.* **1997**, *38*, 3243; d) J. Person, U. Berg, O. Matsson, *J. Org. Chem.* **1995**, *60*, 5037.

[10] A. Roucoux, J. Schulz, H. Patin, *Chem. Rev.* **2002**, *102*, 3757.

[11] B. Schrick, J. L. Blough, A. D. Jones, T. E. Mallouk, *Chem. Mater.* **2002**, *14*, 5140.

[12] a) M. Badri, J.-J. Brunet, *Tetrahedron Lett.* **1992**, *33*, 4435; b) W. A. Herrmann, V. P. W. Böhm, *J. Organomet. Chem.* **1999**, *572*, 141; c) V. P. W. Böhm, W. A. Herrmann, *Chem. Eur. J.* **2000**, *6*, 1017; d) P. Wasserscheid, W. Keim, *Angew. Chem. Int. Ed.* **2000**, *39*, 3772; e) A. Shaabani, A. Rahmati, *Catal. Lett.* **2005**, *100*, 177; f) S. A. Siddiqui, U. C. Narkhede, S. S. Palimkar, T. Daniel, R. J. Lahoti, K. V. Srinivasan, *Tetrahedron* **2005**, *61*, 3539; g) Y. Huy, J. Chen, Z. G. Le, Q. G. Zheng, *Synth. Commun.* **2005**, *35*, 739; h) S. T. Handy, M. Okello, *J. Org. Chem.* **2005**, *70*, 2874.

[13] J. S. Zhou, G. C. Fu, *J. Am. Chem. Soc.* **2003**, *125*, 14726.