The Cyanation of Aromatic Halides Catalyzed by Nickel(0) Complexes Generated In Situ. III.[#] Kinetic and Mechanistic Aspects

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The cyanation of chlorobenzene catalyzed by $[Ni(PPh_3)_n]$, which was generated in situ from $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 (Ni:Zn:P = 1:3:2 molar ratio), was carried out at 60 °C using KCN or NaCN in hexamethyl phosphoric triamide (HMPA). Kinetic analyses revealed that the reaction rates in the KCN–HMPA system were zero order for both of chlorobenzene and nickel concentrations, and two-thirds order for KCN. The determination of the kinetic order for NaCN was difficult due to its high solubility in HMPA since excess cyanide ion inhibited the reaction. Zinc bromide which was formed with $[Ni(PPh_3)_n]$ from $[NiBr_2(PPh_3)_2]$–Zn–PPh_3, acted as an important cocatalyst for the successful cyanation by comparison with $[Ni(cod)_2]$ (cod = 1,5-cyclooctadiene)–PPh_3 system. Based on these experimental results, a reaction mechanism was proposed and discussed.

The transition metal-catalyzed cyanation of aromatic halides by alkali cyanides has received much attention as a method of preparation of the corresponding nitriles.[1] In previous papers, we reported cyanations of aromatic[2] and vinylic[3] halides by MCN (M = K, Na) that took place in the presence of a catalytic amount of $[Ni(PPh_3)_n]$ generated in situ from $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 (Chart 1). As a noteworthy result, the cyanation of aromatic halides proceeds smoothly by simple mixing of the reactants and the catalytic system in MCN–dipolar aprotic solvents with low cyanide solubility, such as KCN in hexamethylphosphoric triamide (HMPA), or KCN or NaCN in MeCN.[2] On further investigation, we have found that the rate of cyanation of chlorobenzene in the KCN–HMPA system is faster than that of the dissolution of KCN. In this article, the cyanation of chlorobenzene using two systems which have remarkably different cyanide solubility, KCN–HMPA and NaCN–HMPA, was investigated from a kinetic viewpoint to elucidate the reaction mechanism. In addition, the role of zinc salts on the reaction was also examined using $[Ni(cod)_2]$ (cod = 1,5-cyclooctadiene)–PPh_3 as the catalyst.

Results and Discussion

As reported in our previous papers,[#,2] the cyanation of aryl halides by $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 is highly sensitive to both the cyanide solubility and order of addition of the reagents, since free cyanide ion in solution formed less reactive cyanonickel(0) species in the absence of substrates. Therefore, the following two procedures were adopted for the kinetic studies (see experimental for detail). Procedure A: The sequential addition of the aryl halide followed by solid cyanide (within one minute). Procedure B: The sequential addition of cyanide followed by the aryl halide. Procedure A could be used successfully even for higher solubility systems such as NaCN–HMPA (461 mmol dm^{-3} at 60 °C), but Procedure B could be used only for low solubility systems such as KCN–HMPA (1.5 mmol dm^{-3} at 60 °C).

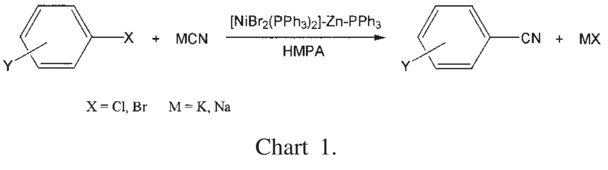

Chart 1.

The effect of the PPh_3 amount in the catalyst component was examined prior to kinetic study in both systems. In the KCN–HMPA system using Procedure B, yields of benzonitrile increased lineally after a short induction period with the ratio of added $PPh_3/Ni = 1$ or 2, as shown in Fig. 1. Higher ratios of external PPh_3/Ni resulted in a longer induction period accompanied by a decrease in the reaction rate of the steady-state nitrile formation.

On the other hand, using NaCN–HMPA by Procedure A, the effect of PPh_3 was not so remarkable in contrast with that in the KCN–HMPA system: Higher ratios of added PPh_3/Ni, from 2 to 12, brought about only a slight decrease in the rates (Fig. 2). Thus, the added PPh_3/Ni ratio of 2 was adopted for further investigation of both systems, and the reaction rates were determined from linear region of time-dependent yields after the induction period.

The Effect of Substituents on Chlorobenzene in the Reaction Rates. The relative rates of the cyanation, R_{ArCl}/R_{PhCl}, were determined by measuring the initial rates of both the individual and competitive reactions with the KCN–HMPA system using Procedure B (Table 1). In the competitive reaction, the relative rates of Y-substituted chlorobenzenes correlated linearly with the Hammet's σ values in the range from $\sigma = -0.27$

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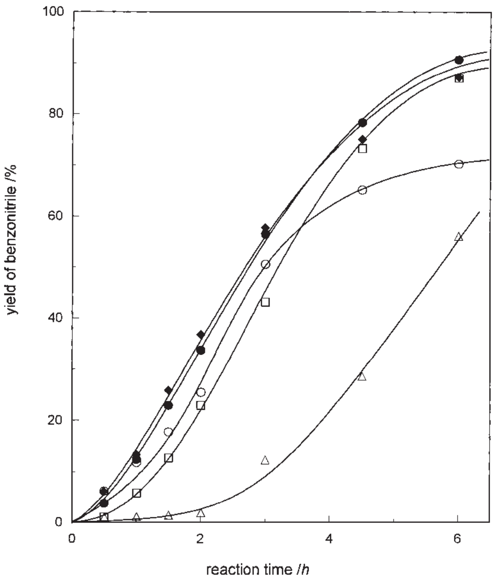


Fig. 1. Effect of PPh_3 addition on cyanation in KCN–HMPA. Carried out by Procedure B. $[NiBr_2(PPh_3)_2]$, 1 mmol (Ni:Zn:P = 1:3:0–8); PhCl, 30 mmol; KCN, 33 mmol; HMPA, 12 cm^3; Temp, 60 °C. Added PPh_3/Ni ratio: -○-, 0; -◆-, 1.0; -●-, 2.0; -□-, 4.0; -△-, 8.0.

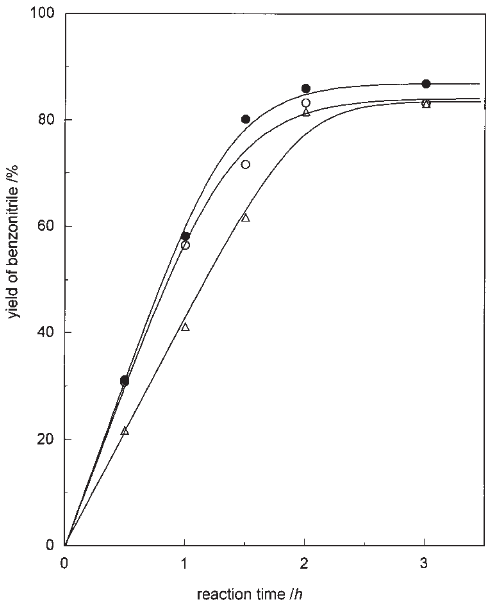


Fig. 2. Effect of PPh_3 addition on cyanation in NaCN–HMPA. Carried out by Procedure A. $[NiBr_2(PPh_3)_2]$, 1 mmol (Ni:Zn:P = 1:3:2–12); PhCl, 30 mmol; NaCN, 33 mmol; HMPA, 12 cm^3; Temp, 60 °C. Added PPh_3/Ni ratio: -●-, 2.0; -○-, 4.0; -△-, 12.0.

Table 1. Relative Rates of Cyanation of Y-Substituted Chlorobenzenes

Y	σ	Relative rate (R_{ArCl}/R_{PhCl})		
		Individual[a)]		Competitive[b)]
		KCN–HMPA	NaCN–HMPA	KCN–HMPA
p-OMe	−0.27	0.90	1.0[c)]	0.41
p-Me	−0.17	0.99		0.64
m-Me	−0.07			0.96
H	0	1	1[c)]	1
m-OMe	+0.12	1.1		1.2
p-F	+0.34	0.93		3.0
p-CF_3	+0.54	1.1		6.9

a) Carried out by Procedure B. $[NiBr_2(PPh_3)_2]$, 1 mmol (Ni:Zn:P = 1:3:2); ArCl, 30 mmol; MCN, 30 mmol; ArCl–HMPA, 15 cm^3 (total volume); Temp, 60 °C. b) Under conditions as described above, except that each 15 mmol of ArCl and PhCl was used. c) Carried out by Procedure A.

(*p*-OMe) to $\sigma = +0.54$ (*p*-CF_3). The resultant positive ρ value (+1.4) indicated that the relative reactivity in the competitive reactions reflected the relative rates of the oxidative addition of the aryl halides to Ni(0), which were accelerated by electron-withdrawing substituents.[4,5] In the individual reactions, however, the relative rates did not vary with the σ values, being about 1.0 in the range of −0.27 (Y = *p*-OMe) to +0.54 (*p*-CF_3). A similar insensitivity to the substituents was also observed in the individual reactions using the NaCN–HMPA system with a high cyanide solubility. These results suggest that the oxidative addition of chlorobenzenes to the Ni(0) species, which plays the main role in the competitive reactions, is not the rate-determining step in the over all catalytic reaction in both systems.

Kinetics. The rate measurements were made for the cyanation of chlorobenzene in the KCN–HMPA and NaCN–HMPA systems. As standard conditions, [PhCl] = 2.0 M (1 M = 1 mol dm^{-3}), MCN = 3.0×10^{-2} mol (equivalent to chlorobenzene), [Ni] = 6.7×10^{-2} M (PhCl/Ni = 30), total volume of PhCl and HMPA = 15 cm^3, using Procedure B for the KCN–HMPA system and Procedure A for the NaCN–HMPA.

KCN–HMPA System: As shown in Fig. 3, the initial rate for the formation of benzonitrile was independent of the initial concentration of chlorobenzene, which ranged from 0.67 to 2.7 M. On the other hand, the rate increased non-linearly with the amount of KCN. The slope of the log[rate] vs log[KCN] plots revealed that the rates obey a two-thirds order relationship with the amount of KCN, as illustrated in Fig. 4. A linear relationship was observed between the rates and the concentrations of the nickel catalyst (Fig. 5).

Eq. 1 shows the rate expression determined experimentally, where $[Ni]_0$ stands for the initial concentration of nickel cata-

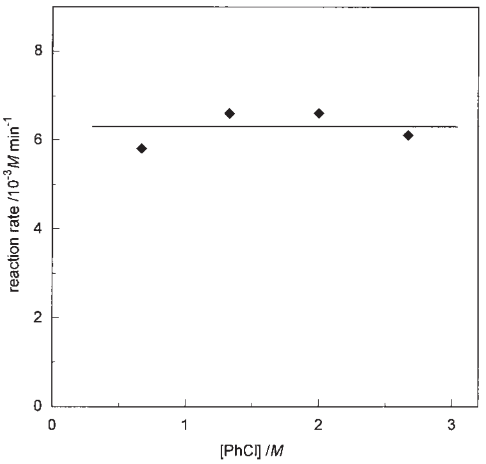


Fig. 3. Plot of rate against chlorobenzene concentration. Carried out by Procedure B. [Ni], 6.7×10^{-2} M (Ni:Zn:P = 1:3:2); KCN, 3.0×10^{-2} mol; PhCl–HMPA, 15 cm^3 (total volume); Temp, 60 °C.

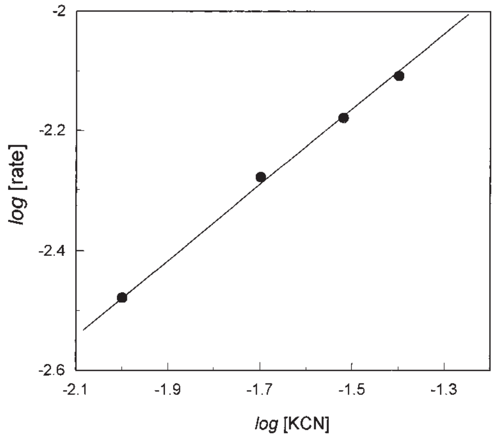


Fig. 4. Plot of log(Rate) against log(KCN/mol). Carried out by Procedure B. [Ni], 6.7×10^{-2} M; [PhCl], 2.0 M; PhCl–HMPA, 15 cm^3; Temp, 60 °C.

lyst and $[M_{\mathrm{KCN}}]$ is the molar amount of KCN in the reaction mixture.

$$\mathrm{Rate} = \mathrm{d}[\mathrm{PhCN}]/\mathrm{d}t = k[\mathrm{Ni}]_0[M_{\mathrm{KCN}}]^{2/3} \quad (1)$$

Here, $[M_{\mathrm{KCN}}]^{2/3}$ is proportional to the surface area of KCN in the solid state. The initial rate of the dissolution of KCN (3×10^{-2} mol) into a mixture of PhCl (3 cm^3) and HMPA (12 cm^3) was determined to be 3.0×10^{-4} M min^{-1} from the solubility vs time plots,[6] which is far smaller (1/10–1/30) than the rates of formation of benzonitrile (2.8×10^{-3}–9.1×10^{-3} M min^{-1}, Fig. 5). This result suggests that the cyanide ions which contribute to the reaction come directly from the solid KCN (KCN$_\mathrm{S}$).

NaCN–HMPA System: In this system, the cyanation was restricted to a narrow zone of NaCN concentration, and proceeded smoothly only in the zone below the dotted line in the presence of 1 mmol of Ni catalyst and 30 mmol of PhCl, as shown in Fig. 6[7] Therefore, kinetic measurements were made only in the restricted range of [PhCl] = 2.0–3.3 M, NaCN = 0.010–0.030 mol, and [Ni] = 0.033–0.13 M (Table 2). In these ranges, the rate was zero order with respect to chlorobenzene and first order with respect to the nickel catalyst. However, the kinetic order for NaCN was lower than that for $[M_{\mathrm{NaCN}}]^{2/3}$ owing to the effects of high cyanide ion concentration compared with the KCN–HMPA system. The reaction rate in NaCN–HMPA was only about three times faster than that in KCN–HMPA in spite of the high solubility (ca. 300 times).

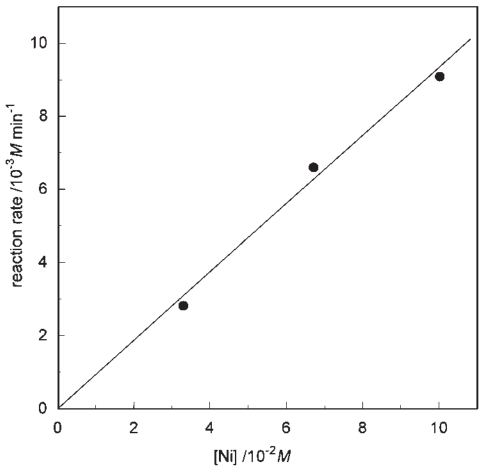


Fig. 5. Plot of rate against nickel concentration. Carried out by Procedure B. [PhCl], 2.0 M; KCN, 3.0×10^{-2} mol; PhCl–HMPA, 15 cm^3; Temp, 60 °C.

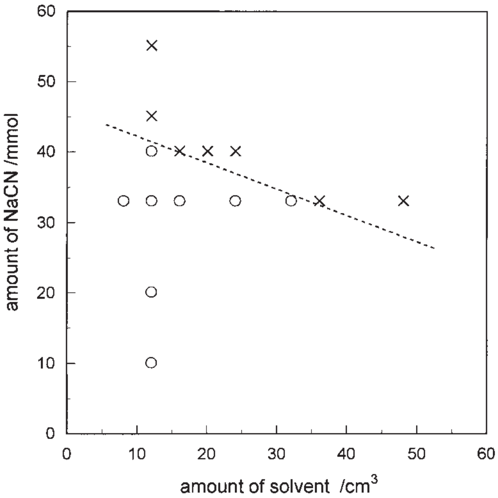


Fig. 6. Reaction zone in NaCN–HMPA system. Carried out by Procedure A. [NiBr$_2$(PPh$_3$)$_2$], 1 mmol (Ni:Zn:P = 1:3:2); PhCl, 30 mmol; Temp, 60 °C. - - -, Border line between reaction and no reaction; ○, Reaction proceeds smoothly; ×, Reaction dose not proceed.

[Ni(cod)$_2$]–PPh$_3$ Catalyst and Effect of ZnBr$_2$ on the Reactivity. In order to clarify the effect of ZnBr$_2$ on the reaction, the cyanation of chlorobenzene was attempted using a modified Procedure B using a [Ni(cod)$_2$]–PPh$_3$ catalyst, which forms [Ni(PPh$_3$)$_n$] without accompanying the formation of ZnBr$_2$ in [NiBr$_2$(PPh$_3$)$_2$]–Zn–PPh$_3$ (Eqs. 2 and 3).[8]

$$[\mathrm{NiBr_2(PPh_3)_2}] + \mathrm{Zn} + \mathrm{PPh_3} \longrightarrow [\mathrm{Ni(PPh_3)}_n] + \mathrm{ZnBr_2} \quad (2)$$

$$[\mathrm{Ni(cod)_2}] + \mathrm{PPh_3} \longrightarrow [\mathrm{Ni(PPh_3)}_n] \quad (3)$$

Table 2. Kinetic Results of the Cyanation of Chlorobenzene in NaCN–HMPA System[a)]

[PhCl] /M	NaCN /mol	$(\mathrm{NaCN/mol})^{2/3}$ /M	[Ni] /M	Rate /M min^{-1}
2.0	0.030	0.10	0.067	0.020
2.7	0.030	0.10	0.067	0.019
3.3	0.030	0.10	0.067	0.020
2.0	0.010	0.046	0.067	0.012
2.0	0.020	0.074	0.067	0.016
2.0	0.030	0.10	0.067	0.020
2.0	0.030	0.10	0.033	—[b)]
2.0	0.030	0.10	0.067	0.020
2.0	0.030	0.10	0.13	0.035

a) Carried out by Procedure B. PhCl–HMPA, 15 cm^3; Temp, 60 °C. b) No reaction.

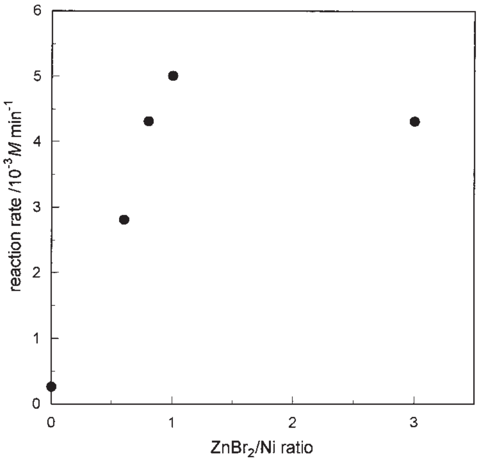


Fig. 7. Effect of $ZnBr_2$ addition on the rate of cyanation in KCN–HMPA with $[Ni(cod)_2]$–PPh_3 catalyst. Carried out by a modified Procedure A. $[[Ni(cod)_2]]$, 6.7×10^{-2} M (Ni:P = 1:4); [PhCl], 2.0 M; KCN, 3×10^{-2} mol; PhCl–HMPA, 15 cm^3; Temp, 60 °C.

As shown in Fig. 7, with the KCN–HMPA system, the addition of $ZnBr_2$ accelerated the reaction remarkably. The reaction rate increased linearly with an increase of the $ZnBr_2$/Ni ratio from 0 to 1. The rate at the ratio of 1 (5.0×10^{-3} M min^{-1}) was almost the same as that for the $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 catalyst (6.6×10^{-3} M min^{-1}), and was 25 times faster than that in the absence of $ZnBr_2$. However, the rate at the ratio of 3 was somewhat lower compared to that at the ratio of 1. Furthermore, with the $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 catalyst, the reaction rate was scarcely accelerated by an equimolar addition of $ZnBr_2$. These results suggest that the acceleration of the reaction is due to the action of any adduct formed by $ZnBr_2$ with a nickel intermediate, $[PhNiCl(PPh)_2]$ (Eq. 4).[9]

$$[PhNiCl(PPh_3)_2] + ZnBr_2 \longrightarrow [Ph\text{-}Ni(PPh_3)_2Cl\text{–}ZnBr_2] \quad (4)$$

A cation exchange of KCN to $Zn(CN)_2$ could be considered as a possible role of the Zn salt, which has been proposed for the Pd catalyzed cyanation using cocatalyst (CuX_2 or ZnX_2).[10] Indeed, the efficiency of $Zn(CN)_2$ as a cyanide source has been generally accepted for the Pd catalyzed reaction.[11] However, this possibility would not be the case for the present Ni catalyzed reaction on the basis of the kinetic result, which indicated that the reaction proceed via cyanide anion abstraction from the solid KCN surface, as mentioned above.

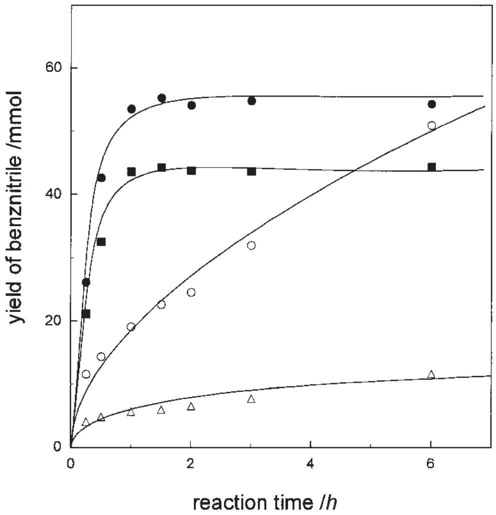
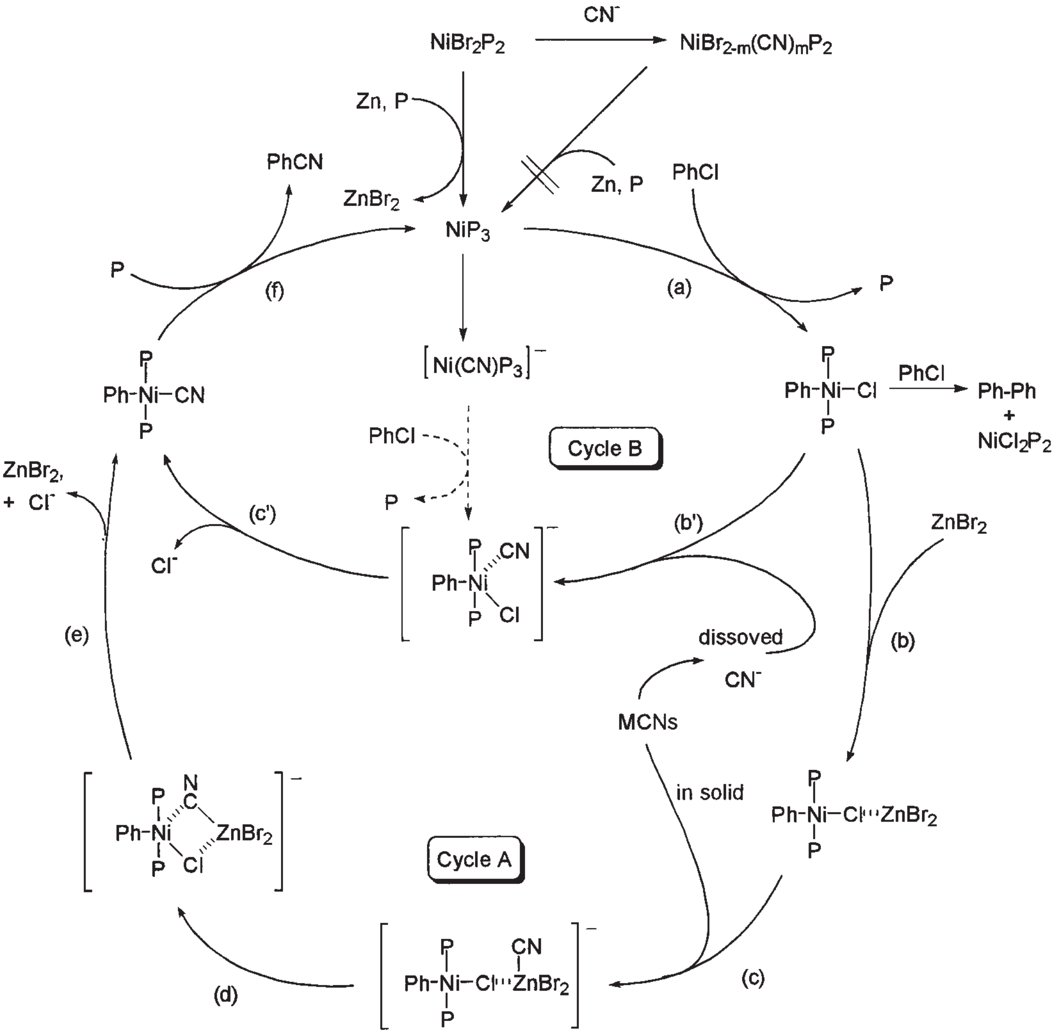


Fig. 8. Effect of $ZnBr_2$ addition on the cyanation in NaCN–HMPA with $[Ni(cod)_2]$–PPh_3 catalyst. Under conditions as described in Fig. 7 except that NaCN was used instead of KCN. $ZnBr_2$/Ni ratio: -○-, 0; -■-, 0.5; -●-, 1.0; -△-, 3.0.

In NaCN–HMPA, the cyanation proceeded fairly smoothly without the addition of $ZnBr_2$, in contrast to the KCN–HMPA system (Fig. 8). This implies that the dissolved cyanide ions largely contribute to the reaction. On the other hand, the addition of $ZnBr_2$ in $ZnBr_2$/Ni = 0.5 or 1.0 accelerated the reaction at an early stage, but the reaction stopped at about 50% and 60% conversion, respectively. Furthermore, a large amount of $ZnBr_2$, for example, $ZnBr_2$/Ni = 3, inhibited rather than accelerated the reaction. Similarly an equimolar addition of $ZnBr_2$ into the $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 catalyst system inhibited the reaction remarkably. One possible interpretation for these effects is any adduct formation of PPh_3 with $ZnBr_2$, which would result in a decrease in free PPh_3 in solution leading to a less active nickel(0) species, such as $[Ni(CN)(PPh_3)_3]^-$ from $[Ni(PPh_3)_3]$ with CN^-. As strong support for the above view, it was observed that the reaction proceeds smoothly even in NaCN–HMPA with the $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 catalyst in the case of further addition of PPh_3 with $ZnBr_2$ (2:1 molar ratio), but does not proceed in the case of addition of $ZnBr_2$



Scheme 1. Reaction mechanism.

alone.[12]

Mechanistic Consideration. On the basis of the experimental results, the mechanism as shown in Scheme 1 is proposed as the most plausible one for the cyanation. The nickel catalyst, $[Ni(PPh_3)_4]$, which dissociates into $[Ni(PPh_3)_3]$ in solution,[13,14] is easily formed by the reduction of $[NiBr_2(PPh_3)_2]$ with Zn dust in the presence of PPh_3. As reported previously, the presence of excess cyanide ion formed a less reactive cyanonickel(0) complex, $[Ni(CN)(PPh_3)_3]^-$,[2] and therefore it is necessary for the successful cyanation in NaCN–HMPA to adopt Procedure A under limited conditions (Fig. 6). On the other hand, in the KCN–HMPA system, the cyanation proceeds smoothly by any procedure attempted.

The paths of cyanation are shown by two catalytic cycles, A and B in Scheme 1. In both cases, the reaction is initiated by the oxidative addition of chlorobenzene to $[Ni(PPh_3)_3]$ (step (a)). The addition product, $[PhNiCl(PPh_3)_2]$, is converted into $[PhNi(CN)(PPh_3)_2]$ via the reaction with MCN_S in the presence of $ZnBr_2$ as promoter (steps (b)–(e) in Cycle A) or via the reaction with the dissolved CN^- (steps (b′), (c′) in Cycle B). In the last step, $[PhNi(CN)(PPh_3)_2]$ undergoes reductive elimination to give benzonitrile and $[Ni(PPh_3)_3]$ (step (f)), and the catalytic reaction is recycled.

Cycle A would play the main role in the KCN–HMPA system, because the dissolution rate of KCN and the reaction rate with the $[Ni(cod)_2]$–PPh_3 catalyst in the absence of $ZnBr_2$ is very slow. The oxidative addition of chlorobenzene to $[Ni(PPh_3)_3]$ (step (a)) is known to be very fast.[4,15] In accordance with this, the overall rate of the cyanation was independent of the concentrations of chlorobenzene (Fig. 3) and of the kinds of substituted chlorobenzenes. However, significant differences in the relative rate of substituted chlorobenzenes in the competitive reaction imply that their ability towards the oxidative addition becomes a dominant factor.[4,5] In the next step (b), $[PhNiCl(PPh_3)]$ forms an adduct with $ZnBr_2$ (Eq. 4) and the adduct draws out CN^- from the surface of solid KCN by an interaction between the Zn atom and KCN. Here, assuming that this step (c) is the rate-determining step, the derivable rate equation is in accord with Eq. 1. Subsequently, the CN^- coordinated adduct is converted into $[PhNi(CN)(PPh_3)_2]$ via a cyano-bridged nickel complex[16] (steps (d), (e)). In connection with the last step (f), being a so-called reductive elimination, it is well known that phosphorus ligands accelerate the reductive elimination of nitriles from cyanoarylnickel[17] and cyanoalkylnickel[18] complexes. In our case, however, large amounts of triphenylphosphine retarded the reaction in the early stage rather than contributing to the rate enhancement (Fig. 1). This suggests that the step (f) is not the rate-determining step. The oxidative addition of benzonitrile to the Ni(0) species appears to be difficult compared with that of chlorobenzene.[19,20] In fact, we ascertained that benzonitrile failed to undergo an oxidative addition under our reaction conditions.

In the NaCN–HMPA system, Cycle B would participate in the reaction together with Cycle A, given that the reaction proceeds fairly smoothly in the absence of $ZnBr_2$ (cf. Fig. 8). $[PhNiCl(PPh_3)_2]$ reacts with the dissolved CN^- to give $[PhNi(CN)(PPh_3)_2]$ (steps (b′), (c′)) probably via a CN-coordinated intermediate (so-called association path).[21,22] The substitution can be assumed to be a rapid reaction judging from the fact that the Cl substitution of *trans*-$[(p\text{-}C_6H_4Me)NiCl(PEt_3)_2]$ by CN^- in EtOH proceeds rapidly.[21] With this system, both the dissolution of NaCN and the abstraction of CN^- from the surface of KCN_S by the $[PhNiCl(PPh_3)_2\text{–}ZnBr_2]$ adduct appear to act as the rate-determining step.

Experimental

Materials. HMPA and chlorobenzene were distilled after drying over Molecular Sieve 13X and the former was stored in the presence of the drying agent. The other substituted chlorobenzenes from commercial sources were used without further purification. KCN and NaCN were ground by the use of a mortar and were sieved to obtain 350–250 µm (40–60 mesh) fractions. Zn dust, PPh_3, $ZnBr_2$ (anhydride), and $[Ni(cod)_2]$ were commercially available. $[NiBr_2(PPh_3)_2]$ was prepared by a literature method.[23]

General Procedure for the Cyanation Catalyzed by $[NiBr_2(PPh_3)_2]$–Zn–PPh_3. Procedure A: $[NiBr_2(PPh_3)_2]$ (740 mg, 1.0 mmol), Zn dust (200 mg, 3.0 mmol), and PPh_3 (520 mg, 2.0 mmol) were placed in a 50 cm^3 flask equipped with a magnetic stirrer, a three-way cock, and an MCN container connected by means of a ground-glass joint. After replacing the air with nitrogen, HMPA was added by a syringe. The mixture was then kept at 60 °C for 30 min while stirring, chlorobenzene (3.38 g, 30 mmol) and naphthalene (0.2 g, GC internal standard) were added, followed by MCN (33 mmol) (within one minute) from the MCN container. The reaction mixture was kept at 60 °C. Small aliquots of the mixture were withdrawn at appropriate time intervals, poured into a small amount of CH_2Cl_2, and, after bubbling with air, subjected to GC analysis (3 m EGS column, He carrier gas, 150 °C).

Procedure B: This procedure was the same as Procedure A, except that the order of the addition of chlorobenzene and MCN was reversed.

Relative Rate of Substituted Chlorobenzenes. The reaction was carried out using Procedure B. In all cases, the total volume of substrate and HMPA was adjusted to 15 cm^3. In the competitive reaction, a mixture of equimolar amounts of two chlorides was used. The initial rates were calculated from the slope of the time to yield plots at an early stage of the reaction (Table 1).

Kinetic Measurement. With KCN–HMPA, the reaction was carried out using Procedure B, while with the NaCN–HMPA system, it was carried out using Procedure A. The standard reaction mixture was composed of 740 mg (1.0 mmol) of $[NiBr_2(PPh_3)_2]$, 200 mg (3.0 mmol) of Zn dust, 520 mg (2.0 mmol) of PPh_3, 3.38 g (30 mmol) of chlorobenzene, 1.95 g (30 mmol) of KCN or 1.47 g (30 mmol) of NaCN, and 12 cm^3 of HMPA (total volume of chlorobenzene and HMPA was adjusted to 15 cm^3). The reaction was carried out at 60 ± 1 °C. The amounts of chlorobenzene, MCN, and $[NiBr_2(PPh_3)_2]$–Zn–PPh_3 (Ni:Zn:P = 1:3:2) were varied as indicated in Figs. 3, 4, and 5 for the KCN–HMPA system and in Table 1 (and Fig. 6 as reference experiment) for the NaCN–HMPA system. The reaction rates were measured in a similar manner as above.

General Procedure for the Cyanation Catalyzed by $[Ni(cod)_2]$–PPh_3–$ZnBr_2$. The reaction was carried out using a modified Procedure A described below. After a prescribed amount of $ZnBr_2$ (0–3 mmol) was placed in a flask filled with nitrogen, a solution of $[Ni(cod)_2]$ (2.75 g, 1.0 mmol) and PPh_3 (1.05 g, 4.0 mmol) in HMPA (12 cm^3) was added, and the mixture was then kept at 60 °C for 30 min while stirring. Chlorobenzene (3.38 g, 30 mmol) was added, followed immediately by MCN (30 mmol) from the MCN container. The reaction mixture was kept at 60 °C. The variation in yield with time was followed by GC analysis (Figs. 7 and 8).

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