3282 *Organometallics* **1996,** *15,* 3282−3288

Lewis Acid Promoted, Nickel Cyanide Catalyzed Double Insertion of Carbon Monoxide in Reaction with Alkynols Using PEG-400 as a Phase-Transfer Agent. Role of Phase-Transfer Catalysts in Determining the Stereochemistry of the Reaction

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Received March 25, 1996[⊗]

Alkynols can be converted to 2-alkylidenebutanedioic acids in excellent yield by $Ni(CN)_2$-catalyzed reactions in toluene and 5.0 M aqueous NaOH under atmospheric pressure of CO at 95 °C, with polyethylene glycol (PEG-400) as the phase-transfer agent. This process is accelerated by the addition of certain Lewis acids, including $CeCl_3{\cdot}7H_2O$, $FeCl_3$, and $LaCl_3{\cdot}7H_2O$. The extent of conversion and the selectivity of the reaction are sensitive to the concentration of base. The stereochemistry for the formation of diacids using PEG-400 as the phase transfer agent is opposite to that found with quaternary ammonium salts. *E*-unsaturated diacids are the dominant products in all cases when PEG-400 is used as the phase-transfer agent.

Phase-transfer catalysis is a versatile and important synthetic technique in organic chemistry.[1−6] Quaternary ammonium salts are the most commonly used phase-transfer agents.[1−5] Crown ethers have also been utilized as phase-transfer catalysts for a variety of organic reactions,[2,3,7] although they are relatively expensive and toxic in some cases. Polyethylene glycols (PEGs) have received increasing attention as phase-transfer catalysts in recent years, since Lehmkuhl and co-workers demonstrated that PEGs were excellent catalysts for substitution reactions of benzyl bromide.[8] In addition to their low cost and apparent lack of significant toxicological properties, PEGs are efficient phase-transfer catalysts in numerous organic transformations,[7,9−38] as well as good host solvents and catalyst, in some cases.[16,39] Often considered as acyclic crown ether analogs,[7,12,15] PEGs are excellent substitutes for crown ethers in a variety of phase-transfer reactions,[9−19] as well as useful alternative phase-transfer catalysts to quaternary ammonium salts in many instances.[26,29,32−34,37] For example, PEGs are as efficient as the latter for manganese carbonyl induced conversion of alkynes to lactones,[33] the cobalt carbonyl catalyzed carbonylation of thiiranes,[34] and the carbonylation of iodoarenes and iodoalkanes.[37] There are instances where PEGs are clearly superior to quaternary ammonium salts, e.g. the dehydrohalogenation of (2-bromoethyl)benzene and the autoxidation of diphenylmethane.[26] In the palladium chloride catalyzed oxi-

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[⊗] Abstract published in *Advance ACS Abstracts,* June 15, 1996.

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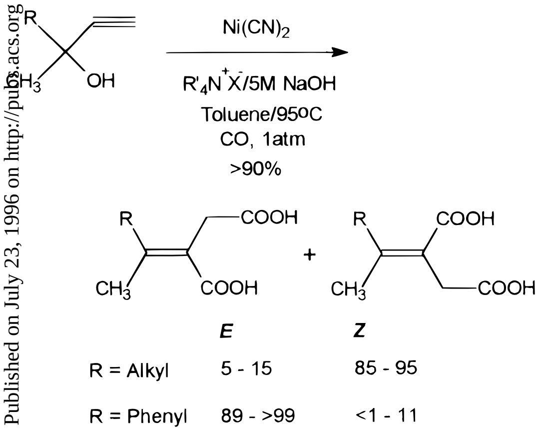
S0276-7333(96)00222-1 CCC: $12.00

dation of olefins to carbonyl compounds, only terminal olefins are converted to ketones using a quaternary ammonium salt (such as cetyltrimethylammonium bromide) as the phase-transfer catalyst,[40] while the reaction proceeds smoothly for both internal and terminal olefins, with a faster reaction rate observed for terminal olefins, using PEG-400 as the phase-transfer agent.[32]

Recently, nickel cyanide was found to be an active catalyst precursor for the carbonylation of a variety of halides,[41-48] alcohols,[49,50] alkynes,[51,52] and allenes,[53] to give different classes of acids under phase-transfer conditions. The key catalytic species is the cyanotricarbonylnickel anion, $[Ni(CN)(CO)_3]^-$, which has been isolated and characterized as the bis(triphenylphosphine)nitrogen (1+) salt.[41] Quaternary ammonium salts were used as the phase transfer catalysts in all cases, except the carbonylation of dibromocyclopropanes, where PEG-400 was the phase-transfer agent.[38] Interestingly, Lewis acids (such as lanthanide salts) greatly accelerate the $Ni(CN)_2$-catalyzed carbonylation of benzyl chlorides.[43] Similar Lewis acid effects have also been demonstrated in cobalt-catalyzed carbonylation[37] and hydrogenation[36] reactions under phase-transfer conditions.

The carbonylation of alkynols was effected using $Ni(CN)_2$ as the catalyst, in toluene and aqueous sodium hydroxide (5 M), with different quaternary ammonium salts as the phase-transfer catalysts at 95 °C, affording the corresponding unsaturated diacids in excellent yield and stereoselectivity (eq 1).[50] When R = alkyl, the *Z* isomers are the major products in >85% selectivity, while the *E* isomer is obtained as the major product when R = phenyl. It was of interest to investigate whether PEG could promote the carbonylation of alkynols under basic conditions. Herein, we report the $Ni(CN)_2$- and PEG-400-catalyzed carbonylation of alkynols, which is accelerated significantly by added Lewis acids. Furthermore, the *E*/*Z* selectivity of the unsaturated diacids obtained from the $Ni(CN)_2$- and PEG-400-catalyzed carbonylation of alkynols where R = alkyl is opposite to that of quaternary ammonium salts.[50] These are the first examples clearly demonstrating how a phase-transfer reagent can affect the stereochemistry of a metal-catalyzed process.



(1)

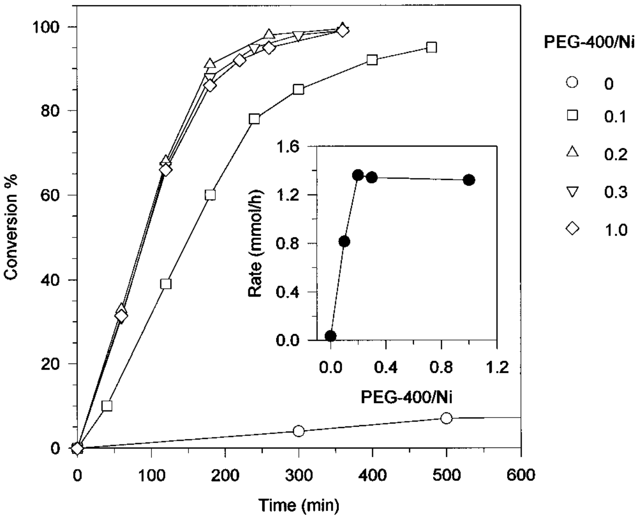
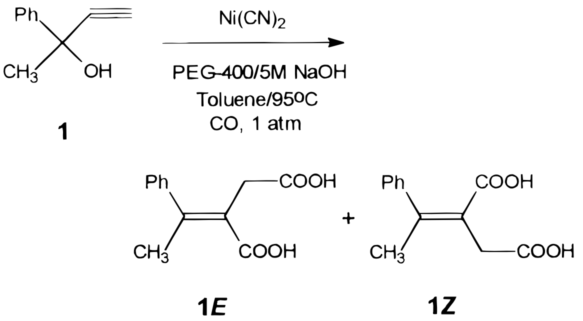


Figure 1. Effect of the concentration of PEG-400 on the carbonylation of 2-phenyl-3-butyn-2-ol (**1**). Conditions: substrate, 4.0 mmol; $Ni(CN)_2$, 0.4 mmol; 5 M NaOH, 10 mL; toluene, 20 mL; CO, 1 atm; temperature, 95 °C.

Results and Discussion

The influence of phase-transfer agent and base concentration, as well as Lewis acids was examined using 2-phenyl-3-butyn-2-ol (**1**) as the reactant alkynol.

1. Concentration Effect of PEG-400. Treatment of 2-phenyl-3-butyn-2-ol (**1**) (4.0 mmol) with carbon monoxide (1 atm) in 10 mL of 5.0 M NaOH and 20 mL of toluene (eq 2), in the presence of $Ni(CN)_2$ (0.4 mmol) at 95 °C *without* PEG-400, afforded only 9% conversion of **1** after 24 h. However, repetition of the reaction with 0.04 mmol of added PEG-400 (PEG-400/Ni = 0.1) increased the reaction rate dramatically, as shown in Figure 1. The reaction rate increases when PEG-400/Ni = 0.2, while a further increase in the ratio of PEG-400/Ni (up to 1:1) has little influence on the percent conversion. These trends are appreciably different from the concentration effects found in the $Ni(CN)_2$-catalyzed and quaternary ammonium salt promoted carbonylation of benzyl chloride, where a maximum was observed.[43]



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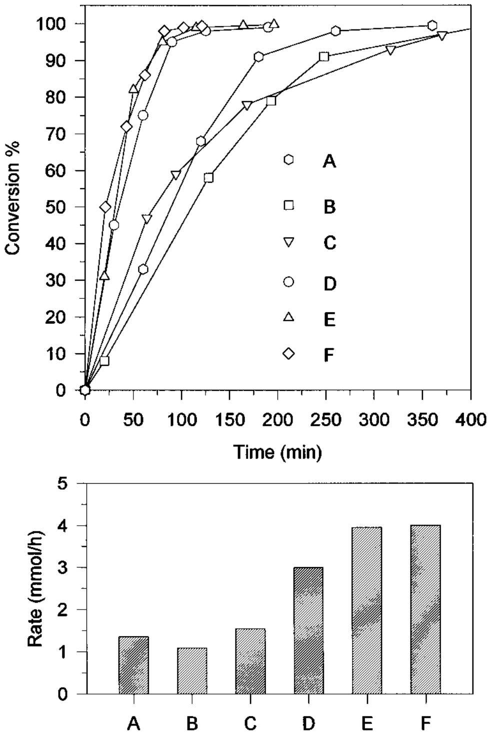

Figure 2. Effect of Lewis acids on the carbonylation of of 2-phenyl-3-butyn-2-ol (**1**): (A) no added Lewis acid; (B) $AlCl_3$; (C) $ZnCl_2$; (D) $CeCl_3{\cdot}H_2O$; (E) $FeCl_3$; (F) $LaCl_3{\cdot}H_2O$. Conditions: substrate, 4.0 mmol; $Ni(CN)_2$, 0.4 mmol; PEG-400, 0.08 mmol; $MCl_n/Ni(CN)_2$, 0.8; 5 M NaOH, 10 mL; toluene, 20 mL; CO, 1 atm; temperature, 95 °C.

The *E*/*Z* ratio ((86 ± 2)/(14 ± 2)) does not change by increasing the ratio PEG-400/Ni from 0.1 to 1.0.

2. Influence of Lewis Acids. Figure 2 illustrates the effects of different Lewis acids on the rate of carbonylation of **1**. Although the addition of $AlCl_3$ (B) or $ZnCl_2$ (C) is not beneficial to the reaction, the carbonylation is promoted significantly by the addition of $CeCl_3{\cdot}7H_2O$, $FeCl_3$, or $LaCl_3{\cdot}7H_2O$, with $LaCl_3{\cdot}7H_2O$ being the most effective Lewis acid. These observations may be explained on the basis of relative stability constants of metal cyanide and by the ability of metal ions to form metalates under basic conditions. The relative amount of $[Ni(CO)_3(CN)]^-$ in the aqueous–organic interface apparently governs the rate of the reaction, with $[Ni(CO)_3(CN)]^-$ brought into the interface by PEG-400 via the formation of a $[\text{PEG-400}-Na]^+[Ni(CO)_3(CN)]^-$ ion pair.[18] The amphoteric behavior of the Al^{3+} ion results in the formation of $[Al(OH)_4(H_2O)]^-$ (or AlO_2^-), and there is a lack of coordinating ability of Al^{3+} with CN^- in strong base.[54] The aluminate anion may compete with $[Ni(CO)_3(CN)]^-$ in the ion pair noted, and as a result, the carbonylation reaction rate is retarded slightly as $AlCl_3$ is added to the reaction system.

The addition of other Lewis acids to the reaction system may be rationalized in the following ways. (i) Although the stability constants for cerium and lanthanum cyanides, as well as the consecutive constants for a number of Lewis acids, are not available,[54] the cumulative stability constants of Fe^{3+} ($\beta_6 = 44$), Ni^{2+} ($\beta_4 = 22$), and Zn^{2+} ($\beta_4 = 17$) with CN^- anion[54] may be indicative of the relative carbonylation reaction rate. Since the cumulative stability constants are normally dominated by the first and the second consecutive stability constants, their magnitudes reflect qualitatively the relative binding ability of the metal ion with the ligands, even though the coordination number is different in some cases. The binding ability of Zn^{2+} with CN^- ($\beta_4 = 17$) is comparable to that of Ni^{2+} with CN^- ($\beta_4 = 22$), and thus the addition of $ZnCl_2$ to the system does not impact greatly on the extent of conversion of the alkynol. The coordination of CN^- to Fe^{3+} ($\beta_6 = 44$) is much stronger than that to Ni^{2+}, and therefore addition of $FeCl_3$ to the reaction system promotes the formation of the active species $[Ni(CO)_3(CN)]^-$, which in turn accelerates the carbonylation reaction. Similar ion effects may occur for Ce^{3+} and La^{3+}. Note that a blue species is formed in the reaction mixture when $FeCl_3$ is used as the Lewis acid. (ii) The promotion of the carbonylation reaction by the added Lewis acid (especially M^{3+}) suggests the participation of M^{3+} in the $[\text{PEG-400}-M]^{3+}[Ni(CO)_3(CN)]^-_x$ ($x > 1$) ion pair, which increases the concentration of $[Ni(CO)_3(CN)]^-$ anion in the interface. (iii) It is conceivable that the Lewis acid coordinates to $[Ni(CO)_3(CN)]^-$ via the lone pair on the cyanide nitrogen atom, facilitating the carbonyl insertion process as previously proposed.[43]

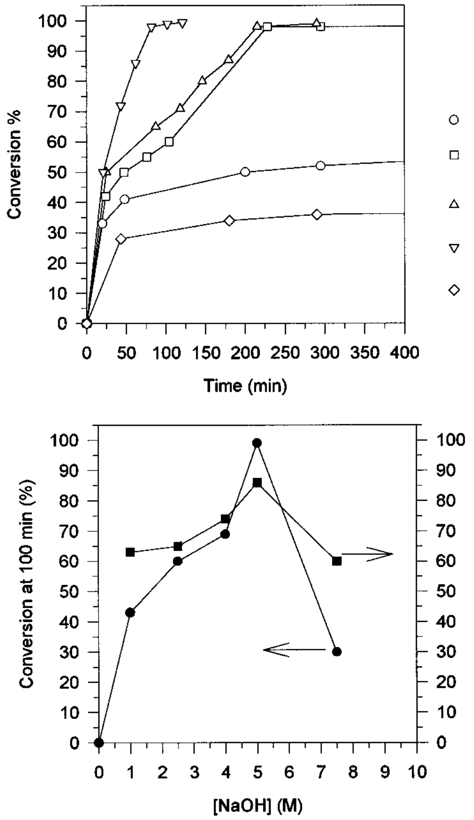

Figure 3. Effect of base concentration on the carbonylation of of 2-phenyl-3-butyn-2-ol (**1**). Conditions: substrate, 4.0 mmol; $Ni(CN)_2$, 0.4 mmol; PEG-400, 0.08 mmol; $LaCl_3{\cdot}7H_2O/Ni(CN)_2$, 0.8; aqueous phase, 10 mL; toluene, 20 mL; CO, 1 atm; temperature, 95 °C.

3. Effect of Base Concentration. The concentration of NaOH has a dramatic influence on both the reaction conversion and selectivity. No reaction was observed in the absence of NaOH. When 1.0 M NaOH was used as the aqueous phase, only about 40% conversion was reached, and prolonged stirring did not increase the conversion. The percent conversion increases

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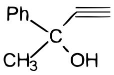
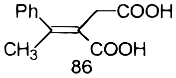
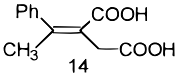
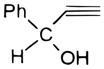
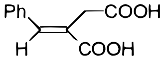
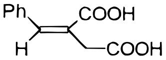
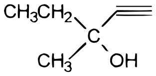
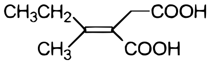
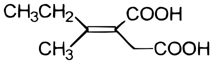
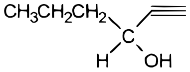
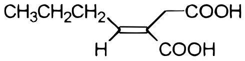
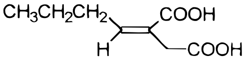
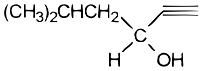
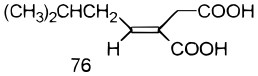
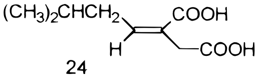
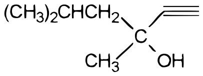
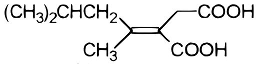
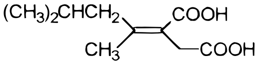
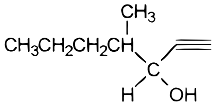
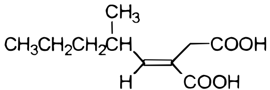
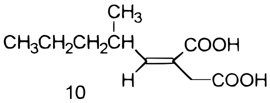
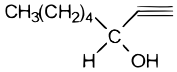
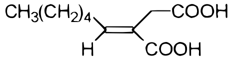
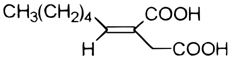
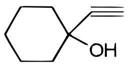
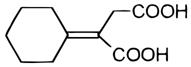
Table 1. Carbonylation of Different Alkynols to Diacids[a]

No.	Alkynols	Yield (%)[b]	Diacids (%)[c]	
			E	*Z*
1		95	 86	 14
2		92	 88	 12
3		84	 65	 35
4		87	 70	 30
5		91	 76	 24
6		97	 80	 20
7		88	 90	 10
8		86	 78	 22
9		90		

[a] Conditions: substrate, 4.0 mmol; Ni(CN)$_2$, 0.4 mmol; PEG-400, 0.08–0.12 mmol; LaCl$_3$·7H$_2$O/Ni(CN)$_2$, 0.8; 5.0 M NaOH, 10 mL; toluene, 20 mL; CO, 1 atm; temperature, 95 °C; time, 4–8 h. [b] Yields are isolated yields before recrystallization. [c] Determined by ^{1}H NMR by comparison with the spectroscopic data in the literature and confirmed by ^{1}H NOE data.

with increasing concentration of NaOH, with >95% conversion reached after 5 h when [NaOH] = 2.5 and 4.0 M. The reaction was complete in 2 h when 5.0 M NaOH was used, while the conversion decreased at high base concentration (7.5 M). A similar base concentration effect was observed in the Ni(CN)$_2$-catalyzed carbonylation of benzyl chloride with $R_4N^+X^-$ as the phase-transfer agent.[43] The same trend was observed for the selectivity of this reaction (eq 2 and Figure 3), with [NaOH] = 5.0 M giving the best results. These observations suggest that 5.0 M base is required for the efficient formation of the catalytic active species, $[Ni(CO)_3(CN)]^-$, but too high a base concentration can depress this process.

Having determined the optimum reaction conditions for the nickel cyanide and PEG-400 catalyzed carbonylation of **1**, a variety of alkynols (**2**–**9**, Table 1) were reacted under the same conditions, affording unsaturated diacids in excellent yield. The stereochemistry (*E* or *Z*) of the produced 2-alkylidenebutanedioic acids was determined by comparison of ^{1}H NMR spectroscopic data with those for known compounds[50] and confirmed by ^{1}H NOE measurements. Consider the NMR of 2-butylidenebutanedioic acid, **4*E***, as a reprsentative example (Scheme 1). Irradiation of the C*H*$_2$COOH signal results in strong enhancement of the resonance of CH$_3$CH$_2$C*H*$_2$, but no enhancement is observed in the signal of C*H*=, indicating that CH$_2$COOH and H on the double bond are *trans* to each other. Therefore, the stereochemistry of the major carbonylation product of 1-hexyn-3-ol (**4**) is assigned as *E*. In addition, the ^{1}H NMR resonance of C*H*$_2$COOH in the *E* isomers of all alkylidenebutanedioic acids is always located at lower field than that in the *Z* isomers (Table 2, entries 3–8); the opposite is true for benzylidenebutanedioic acids (cf. Table 2, entries 1 and 2). The ^{1}H NMR resonance of C*H*= in the *E* isomers of alkylidenebutanedioic acids also occurred at lower field than that of the *Z* isomers (Table 2, entries 4, 5, 7, and 8), providing further

Scheme 1

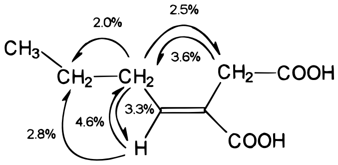
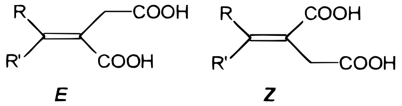


Table 2. Comparison of ^{1}H NMR Resonances of CH_2COOH and CH= Protons in *E* and *Z* Isomers



No	R, R'	δ(CH_2COOH)^a		δ(CH=)^a	
		E	*Z*	*E*	*Z*
1	Ph, CH_3	3.16^b	3.53^b		
		3.26	3.62		
2	Ph, H	3.54	3.60	7.91	7.70
3	CH_3CH_2, CH_3	3.39^b	3.37^b		
		3.39	3.37		
4	$CH_3CH_2CH_2$, H	3.35	3.27	6.94	6.14
5	$(CH_3)_2CHCH_2$, H	3.35	3.29	6.97	6.18
6	$(CH_3)_2CHCH_2$, CH_3	3.42^b	3.39^b		
		3.43	3.38		
7	$CH_3CH_2CH_2\overset{CH_3}{CH}$, H	3.35	3.27	6.71	6.44
8	$CH_3(CH_2)_4$, H	3.34	3.27	6.95	6.15

^{a} Acetone-d_6 as solvent, in ppm. ^{b} $CDCl_3$ as solvent.[50]

support for the assignment of the stereochemistry of alkylidenebutanedioic acids. The *E*/*Z* ratio was determined by ^{1}H NMR integration. A fascinating aspect is the inversion in stereochemistry found when PEG-400 was used as the phase-transfer catalyst instead of quaternary ammonium salts.[50] *E* isomers are the dominant products in all cases using PEG-400, while *Z* isomers are dominant for alkyl-substituted alkynols when quaternary ammonium salts are the phase-transfer agents.[50]

A possible mechanism for the carbonylation reaction is outlined in Scheme 2 (note that dotted lines refer to interactions and not to formal bonding). The first step involves the generation of the cyanotricarbonylnickelate anion, $[Ni(CO)_3(CN)]^-$, in the presence of CO as proposed previously.[41,43,47,48] The $[Ni(CO)_3(CN)]^-$ produced was transferred to the interface by PEG-400 via the formation of an ion pair, $[PEG\text{-}400{-}M^{n+}]{-}[Ni(CO)_3(CN)]^-$ (**10**). The generation of $[Ni(CO)_3(CN)]^-$ in the aqueous phase can be accelerated by the base and Lewis acid, which are consistent with the influence of the base concentration and Lewis acid on the reaction. The Lewis acid may also accelerate the transfer of $[Ni(CO)_3(CN)]^-$ and increase the relative concentration of $[Ni(CO)_3(CN)]^-$ at the interface, which in turn increases the rate of the carbonylation reaction as discussed above. Although the interaction of $[Ni(CO)_3(CN)]^-$ with the metal ion in the ion pair is postulated to occur via the nitrogen lone pair, one cannot rule out coordination by a carbonyl oxygen. The alkynol (RR′C(OH)C≡CH, R > R′) may then incorporate into the ion pair (step **ii**) with the assistance of base to form **11**. Nucleophilic addition of $[Ni(CO)_3(CN)]^-$ to the alkyne carbon with protonation (step **iii**), followed by carbonyl insertion (step **iv**) and then cleavage of the acyl carbon−nickel bond (step **v**), gives **14**. This complex (**14**) may either react with H_2O via step **vi a** to give the α-methylene acid **A** or react with OH^- via step **vi b**, affording **15**, which leads to the formation of diacid. The observation of a small amount of acid **A** during the course of reaction (by GC and ^{1}H NMR in several cases) supports this assumption.

The key step that determines the stereoselectivity may be **viii**, i.e. conversion of **16** to **17**. In **16**, the conjugation of C=C and COO^- forms a plane with R and R′ located on opposite sides. The steric effect of R (R > R′) favors attack by $[Ni(CO)_3(CN)]^-$ at the terminal carbon atom of the carbon−carbon double bond from the opposite face of the R group, i.e. from the front face of the C=CC=O plane. Meanwhile, the static interaction between COO^- and M^{n+} in the emerging ion pair **10** forces the COO^- unit to move toward the ion pair **10** to form complex **17**, which determines the stereoselectivity of the formed diacid. Carbonyl insertion (step **ix**) followed by C−Ni bond cleavage (step **x**) gives the *E*-unsaturated diacid **B**.

The static interaction described above diminishes when a quaternary ammonium salt ($R_4N^+X^-$) is used as the phase-transfer agent. As shown in Scheme 3, $[Ni(CO)_3(CN)]^-$ attacks the terminal carbon on the C=C double bond in **19** from the front face because of the steric effect of the R group. The relative position between R and COO^- is again determined by the steric effect between the R and $-CH_2[Ni(CO)_3(CN)]^-$ moieties, which results in the COO^- group being *cis* to the R group (Scheme 3; **20**). This may account for the stereochemical difference of PEG-400 in comparison with quaternary ammonium salts as phase-transfer agents in the nickel cyanide catalyzed carbonylation of alkynols.

In conclusion, PEG-400 is an excellent phase-transfer agent for the nickel cyanide catalyzed double carbonylation of alkynols to form 2-alkylidenebutanedioic acids. This process is accelerated by the addition of certain Lewis acids, such as $CeCl_3{\cdot}7H_2O$, $FeCl_3$, and $LaCl_3{\cdot}7H_2O$. The stereochemistry for the formation of diacids using PEG-400 as the phase-transfer agent is opposite to that found with quaternary ammonium salts. *E*-Unsaturated diacids are the dominant products in all cases when PEG-400 is used as the phase-transfer agent. These are the first examples, to our knowledge, demonstrating that the choice of phase-transfer agent is central to the stereochemistry of the reaction.

Experimental Section

General Considerations. All ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AMX-500 or Gemini 200 MHz spectrometer using $CDCl_3$ or acetone-d_6 as the solvent. Mass spectra were obtained on a VG 7070 E mass spectrometer. Infrared spectra were run on a Bomem MB-100 FT-IR spectrometer. Alkynols and all other reagents used in this study were purchased from commercial sources and were used as received. Gas chromatographic determinations, used to follow the progress of the reactions, were made on a HP 5890 Series II instrument equipped with a 1.4% OV-17/1.95% OV-210 on Chromosorb W column (T_1 = 70 °C, t_1 = 2 min, dT/dt = 10 °C/min, T_2 = 250 °C, t_2 = 15 min, with triphenylmethane as the internal standard). Anhydrous $Ni(CN)_2$ was prepared by following the literature procedure.[55]

General Procedure for the Phase-Transfer-Catalyzed Carbonylation of Alkynols with $Ni(CN)_2$. To a 100-mL three-necked flask equipped with a stirring bar and condenser was added $Ni(CN)_2$ (0.4 mmol), PEG-400 (0.08−0.12 mmol), $LaCl_3{\cdot}H_2O$ (0.32 mmol), 5.0 M NaOH (10 mL), and toluene

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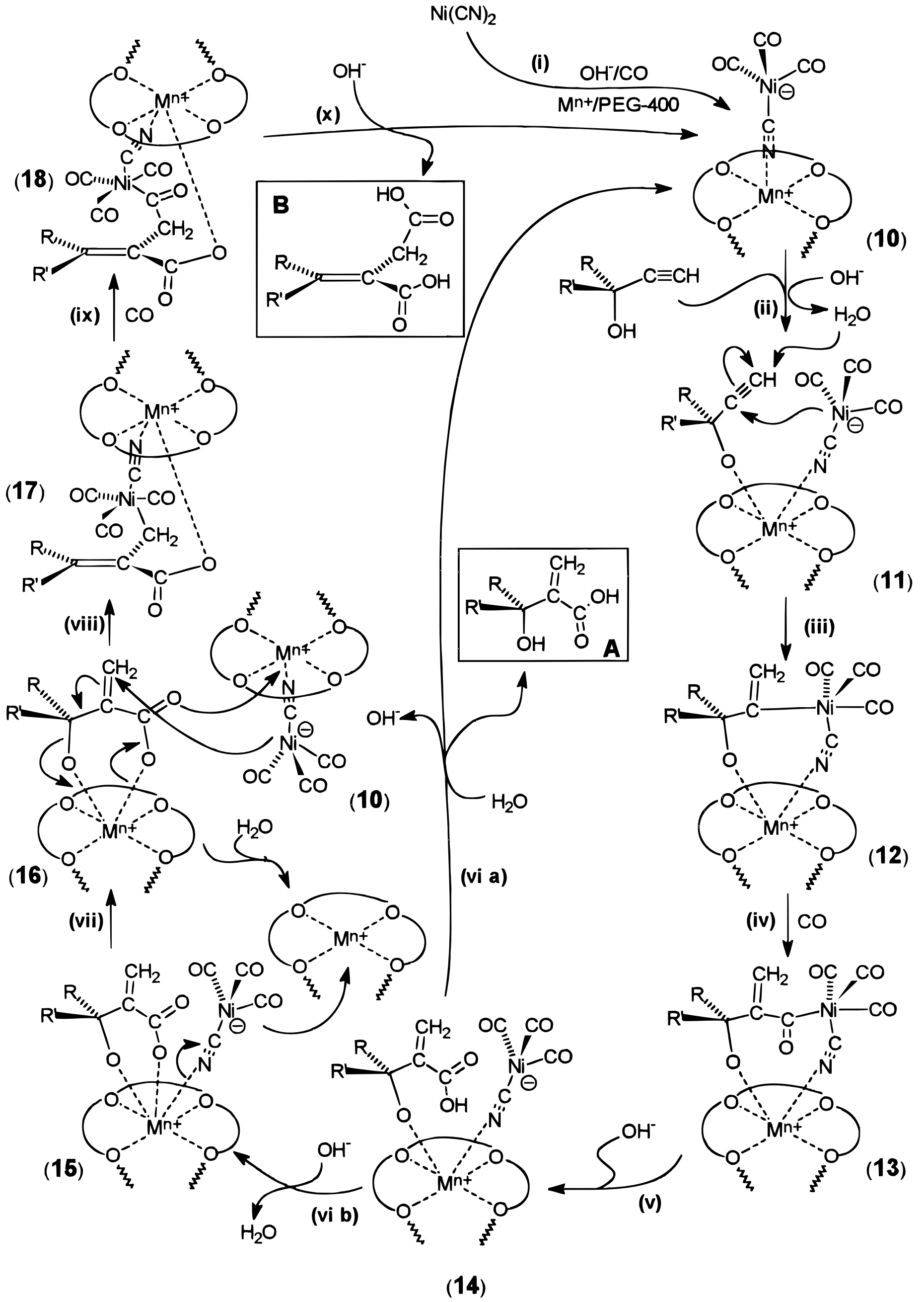
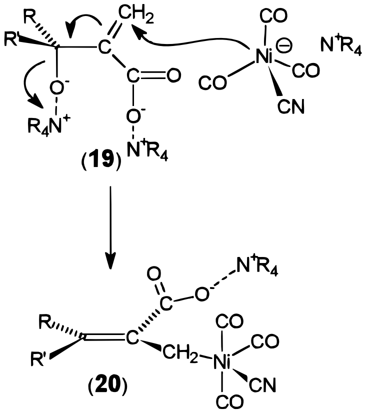
(55) Aynsley, E. E.; Campbell, W. A. *J. Chem. Soc.* **1958**, 1723.

Scheme 2



Scheme 3



(10 mL). The system was flushed with N_2 and then CO for 1 min, the mixture was warmed to 95 °C, and CO was bubbled through the solution slowly for 2 h with stirring. The alkynol (4.0 mmol) and triphenylmethane (0.3 mmol) in 10 mL of toluene were added to the mixture, which was then stirred for another 4–8 h (reaction was monitored by gas chromatography). After the reaction mixture was cooled to room temperature, crushed ice was added, followed by careful acidification with 10% hydrochloric acid. The mixture was extracted with ether or ethyl acetate (3 × 50 mL). The organic extract was then treated with 2 M sodium hydroxide (3 × 15 mL) and the basic extract was acidified with 10% hydrochloric acid in the presence of crushed ice. The diacids were obtained by extracting with ether or ethyl acetate (3 × 50 mL), drying with $MgSO_4$, and removing the solvent by rotary evaporation. Pure acids were isolated by crystallization from ether/*n*-pentane. The spectroscopic data of 2-(1-methylbenzylidene)butanedioic acid (**1*E/Z***),[50] 2-(1-methylpropylidene)butanedioic acid (**3*E/Z***),[50] 2-(1,3-dimethylbutyl)butanedioic acid (**6*E/Z***),[50] and 2-cyclohexylidenebutanedioic acid (**9**)[50,56] are in accord with those reported previously.

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(56) Nogi, T.; Tsuji, J. *Tetrahedron* **1969**, *25*, 4099.

2-Benzylidenebutanedioic Acid (2*E/Z*). Mp: 187−188 °C. IR (ether): ν(C=O) 1716 cm^{-1}; ν(C=C) 1638 cm^{-1}. ^{1}H NMR (acetone-d_6): **2*E***, δ 3.54 (s, 2H), 7.46 (m, 5H), 7.91 (s, 1H); **2*Z***, δ 3.60 (s, 2H), 7.30 (m, 5H), 7.70 (s, 1H). ^{13}C NMR (acetone-d_6): **2*E***, δ 33.83, 127.57, 129.52, 129.78, 129.93, 136.03, 142.18, 169.23, 172.82. MS (*m/e*): 188, [M − H$_2$O]$^+$. Anal. Calcd for $C_{11}H_{10}O_4$: C, 64.07; H, 4.89. Found: C, 64.29; H, 4.75.

2-Butylidenebutanedioic Acid (4*E/Z*). Mp: 153−154 °C. IR (ether): ν(C=O) 1723 cm^{-1}; ν(C=C) 1645 cm^{-1}. ^{1}H NMR (acetone-d_6): **4*E***, δ 0.93 (t, J = 7.4 Hz, 3H), 1.49 (m, J = 7.4 Hz, 2H), 2.21 (q, J = 7.4 Hz, 2H), 3.35 (s, 2H), 6.94 (t, J = 7.5 Hz, 1H); **4*Z***, δ 1.10 (t, J = 7.4 Hz, 3H), 1.36 (m, J = 7.4 Hz, 2H), 2.55 (q, J = 7.4 Hz, 2H), 3.27 (s, 2H), 6.14 (t, J = 7.5 Hz, 1H). ^{13}C NMR (acetone-d_6): **4*E***, δ 14.02, 22.42, 31.33, 32.25, 127.20, 145.77, 168.54, 172.18; **4*Z***, δ 14.02, 23.00, 30.96, 32.07, 126.50, 147.63, 168.00, 173.50. MS (*m/e*): 154, [M − H$_2$O]$^+$. Anal. Calcd for $C_8H_{12}O_4$: C, 55.81; H, 7.02. Found: C, 55.64; H, 6.89.

2-(3-Methylbutylidene)butanedioic Acid (5*E/Z*). Mp: 174−175 °C. IR (ether): ν(C=O) 1719 cm^{-1}; ν(C=C) 1644 cm^{-1}. ^{1}H NMR (acetone-d_6): **5*E***, δ 0.93 (d, J = 6.7 Hz, 6H), 1.78 (m, 1H), 2.14 (t, J = 7.3 Hz, 2H), 3.35 (s, 2H), 6.97 (t, J = 7.6 Hz, 1H); **5*Z***, δ 0.91 (d, J = 6.7 Hz, 6H), 1.56 (m, 1H), 2.48 (t, J = 7.3 Hz, 2H), 3.29 (s, 2H), 6.18 (t, J = 7.6 Hz, 1H). ^{13}C NMR (acetone-d_6): **5*E***, δ 22.60, 28.91, 32.35, 38.26, 127.66, 144.79, 168.56, 172.19; **5*Z***, δ 22.43, 29.23, 32.33, 38.92, 126.83, 146.92, 168.80, 173.50. MS (*m/e*): 168, [M − H$_2$O]$^+$. Anal. Calcd for $C_9H_{14}O_4$: C, 58.05; H, 7.58. Found: C, 58.26; H, 7.52.

2-(2-Methylpentylidene)butanedioic Acid (7*E/Z*). Mp: 164−165 °C. IR (ether): ν(C=O) 1719 cm^{-1}; ν(C=C) 1652 cm^{-1}. ^{1}H NMR (acetone-d_6): **7*E***, δ 0.87 (t, J = 6.7 Hz, 3H), 1.01 (d, J = 6.7 Hz, 3H), 1.32 (m, 4H), 2.55 (m, 1H), 3.35 (s, 2H), 6.71 (d, J = 10.4 Hz, 1H); **7*Z***, δ 2.75 (m, 1H), 3.27 (s, 2H), 6.44 (d, J = 10.1 Hz, 1H), other signals are obscured by those of the major isomer. ^{13}C NMR (acetone-d_6): **7*E***, δ 14.34, 20.18, 21.11, 32.49, 34.02, 39.57, 125.68, 151.36, 168.79, 172.38. MS (*m/e*): 182, [M − H$_2$O]$^+$. Anal. Calcd for $C_{10}H_{16}O_4$: C, 59.98; H, 8.05. Found: C, 59.84; H, 8.17.

2-Hexylidenebutanedioic Acid (8*E/Z*).[48] Mp: 143−144 °C. IR (ether): ν(C=O) 1716 cm^{-1}; ν(C=C) 1631 cm^{-1}. ^{1}H NMR (acetone-d_6): **8*E***, δ 0.93 (t, J = 7.3 Hz, 3H), 1.29, 1.45 (m, 6H), 2.23 (q, J = 7.3 Hz, 2H), 3.34 (s, 2H), 6.95 (t, J = 7.5 Hz, 1H); **8*Z***, δ 2.57 (q, J = 7.3 Hz, 2H), 3.27 (s, 2H), 6.15 (t, J = 7.5 Hz, 1H), other signals are obscured by those of the major isomer. ^{13}C NMR (acetone-d_6): **8*E***, δ 14.20, 23.06, 28.87, 29.32, 32.15, 32.24, 127.02, 145.99, 168.50, 172.12. MS (*m/e*): 182, [M − H$_2$O]$^+$. Anal. Calcd for $C_{10}H_{16}O_4$: C, 59.98; H, 8.05. Found: C, 59.76; H, 8.25.

Acknowledgment. We are indebted to the Natural Sciences and Engineering Research Council of Canada for support of this research.

OM960222Z