APPLIED ORGANOMETALLIC CHEMISTRY
Appl. Organometal. Chem. 2007; **21**: 941–944

(www.interscience.wiley.com) DOI:10.1002/aoc.1314

Nickel-catalyzed coupling of CO_2 and amines: improved synthesis of carbamates

Dong Fang Niu, Li Zhang, Li Ping Xiao, Yi Wen Luo and Jia Xing Lu*

Shanghai Key Laboratory of Green Chemistry and Chemical Process, Department of Chemistry, East China Normal University, Shanghai 200062, People's Republic of China

Received 29 April 2007; Revised 25 June 2007; Accepted 9 July 2007

The electrochemical incorporation of carbon dioxide into amines catalyzed by an electrogenerated Ni complex afforded carbamates in moderate yields under very mild conditions ($p_{CO_2} = 1$ atm, room temperature) without any addition of probases. Mechanistic and electrochemical studies revealed the role of reduced nickel species in the activation of CO_2 and electrogenerated $CO_2^{\cdot-}$ as a base in the synthesis of carbamates. The influence of number of faradays per mole of amine supplied to the electrodes (*Q*), cathode materials, temperatures, supporting salts and amounts of catalyst was studied to optimize the electrolytic conditions. A plausible reaction mechanism for the reduction of CO_2 was proposed. Copyright © 2007 John Wiley & Sons, Ltd.

KEYWORDS: CO_2; Ni complex; electrochemical; synthesis; carbamates

INTRODUCTION

Organic carbamates find several applications in the chemical, pharmaceutical and agricultural industries in the synthesis of intermediates, polymers, medical drugs, pesticides, herbicides and fungicides.[1,2] In classical organic synthesis, this class of compounds finds extensive utilization as protecting groups of the amine functionality in the preparation of polypeptides or other natural substances.[3]

The conventional synthesis of organic carbamates[4] using toxic and harmful reagents (carbon monoxide, phosgene, isocyanates, etc.) under high temperature and pressure has many drawbacks. Carbon dioxide, compared with currently used phosgene and carbon monoxide as C_1-building blocks for chemicals, has the obvious advantage of being non-toxic and easy to handle, transport and store. Feroci *et al.*[5,6] reported the synthesis of carbamates via an electrogenerated base deprotonated amine, yielding the corresponding amine anion, which can then react with carbon dioxide and EtI to give carbamates in moderate yields. In this regard, the electrochemical process, occurring at room temperature and atmospheric pressure of carbon dioxide, is promising; however, it requires the addition of excess probase and a large overpotential for the reduction of probase. The electrochemical reduction of CO_2 has been studied in the last few years.[7–12] However, to the best of our knowledge, there are few scientific works concerning the use of electrogenerated $CO_2^{\cdot-}$ as a strong base[13,14] for carboxylation reaction reported in the literature. In a previous paper,[15] our group reported that electrogenerated base $CO_2^{\cdot-}$ resulting from the reduction of CO_2 at a potential of −2.3 V vs Ag reacts with propylene epoxide under mild conditions, affording the corresponding propylene carbonate. We now wish to report that this method can be extended to the synthesis of carbamates from the corresponding amines. The electroreduction of CO_2 occurred at a mild potential (−1.6 V vs Ag−AgI) in the presence of. $Ni(bpy)_3Cl_2$ complex and a plausible reaction mechanism was proposed.

EXPERIMENTAL

The electrolysis was carried out in DMF-TEABr (20 ml, 0.1 mol/L) containing 0.1 ml of amine in a divided glass cell equipped with gas inlet and outlet. Anolyte and catholyte were separated through a cation-exchange membrane. $Ni(bpy)_3Cl_2$, 5 mmol/l, as catalyst was added to the

---

*Correspondence to: Jia Xing Lu, Shanghai Key Laboratory of Green Chemistry and Chemical Process, Department of Chemistry, East China Normal University, Shanghai 200062, People's Republic of China.
E-mail: jxlu@chem.ecnu.edu.cn
Contract/grant sponsor: Natural Science Foundation of China; Contract/grant number: 20573037.
Contract/grant sponsor: Natural Science Foundation of Shanghai; Contract/grant number: 05JC1407020573037.

catholyte with constant bubbling atmospheric pressure of carbon dioxide to catholyte for 0.5 h, ensuring CO_2 presaturation before electrolysis and providing vigorous stirring throughout the electrolysis. The solution was electrolyzed at room temperature over a copper cathode (12.75 cm^2) and graphite anode (10 cm^2), at a constant potential ($E = -1.6$ V vs Ag–AgI). At the end of the electrolysis, EtI as an alkylating agent was added in 5-fold molar excess, and the catholyte was allowed to reflux at 60 °C, under stirring, for 5 h (Scheme 1). The solvent was removed under reduced pressure, and the residue was washed with aqueous $NaHCO_3$ (10 ml) and extracted with diethyl ether (3 × 20 ml), and the combined organic layers were dried over anhydrous $MgSO_4$. **2a** was determined by GC; **2b–f** were purified by flash chromatography affording pure carbamates. The yields of **2a–f** were based on the starting amines.

*Ethyl phenylcarbamate (**2a**)*

^{1}HNMR ($CDCl_3$): δ (ppm) 7.40–7.10(m, 5H), 6.70(s, 1H), 4.20(q, 2H, $J = 7.1$ Hz), 1.3(t, 3H, $J = 7.1$ Hz); IR(KBr): 1703 cm^{-1} ($\nu_{C=O}$); MS (m/z, %): 165 (M^+, 90), 137 (6), 119 (47), 106 (70), 93 (100), 77 (17), 65 (24), 51 (7), 39 (9), 29 (17).

*Ethyl (p-chloronephenyl) carbamate (**2b**)*

^{1}HNMR ($CDCl_3$): δ (ppm) 7.35–7.20(m,4H), 6.70(s, 1H), 4.21 (q, 2H, $J = 5.9$ Hz), 1.28(t, 3H, $J = 7.2$ Hz). IR(KBr): 1690 cm^{-1} ($\nu_{C=O}$); MS (m/z, %): 199 (M^+, 100), 171 (5), 154 (8), 142 (12), 140 (55), 127 (55), 111 (4), 99 (13), 75 (6), 29 (53).

*Ethyl (p-methoxyphenyl) carbamate (**2c**)*

^{1}HNMR ($CDCl_3$): δ (ppm) 7.20–6.91(m,4H), 6.70(s, 1H), 4.10 (q, 2H, $J = 5.9$ Hz), 3.60(s, 3H), 1.20(t, 3H, $J = 7.2$ Hz). IR(KBr): 1701 cm^{-1} ($\nu_{C=O}$); MS (m/z, %): 195 (M^+, 100), 149 (35), 136 (31), 120 (23), 108 (69), 92 (24), 80 (17), 65 (15), 52 (11), 29 (13).

*Ethyl cyclohexylcarbamate (**2d**)*

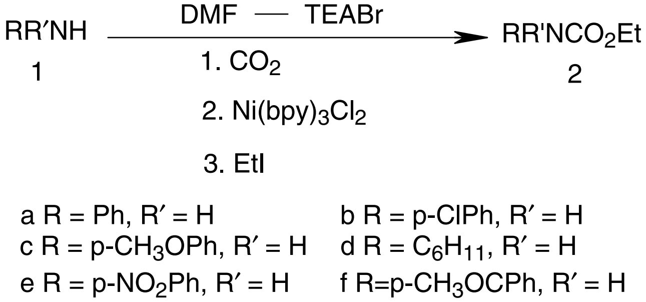
^{1}HNMR ($CDCl_3$): δ (ppm) 4.10(q, 2H, $J = 5.6$ Hz), 3.45 (s, 1H), 3.15(m, 1H), 2.25–1.15(m, 10H), 1.11(t, 3H, $J = 7.5$ Hz); IR(KBr): 1699 cm^{-1} ($\nu_{C=O}$); MS (m/z, %): 171 (M^+, 18), 142 (28), 128 (100), 100 (10), 90 (26), 82 (15), 67 (14), 56 (44), 41 (14), 28 (29).

*Ethyl (p-nitrophenyl) carbamate (**2e**)*

^{1}HNMR ($CDCl_3$): δ (ppm) 8.20–7.80(m,4H), 7.06 (s, 1H), 4.28(q, 2H, $J = 5.9$ Hz), 1.34(t, 3H, $J = 7.2$ Hz). IR(KBr): 1739 cm^{-1} ($\nu_{C=O}$); MS (m/z, %): 210 (M^+, 100), 164 (72), 151 (78), 138 (45), 108 (59), 90 (72), 78 (12), 63 (43), 45 (20), 29 (84).

*Ethyl (p-acetylphenyl) carbamate (**2f**)*

^{1}HNMR ($CDCl_3$): δ (ppm) 7.80–7.59(m,4H), 6.50(s, 1H), 4.25 (q, 2H, $J = 5.9$ Hz), 2.3(s, 3H), 1.25(t, 3H, $J = 7.2$ Hz). IR(KBr): 1725 cm^{-1} ($\nu_{C=O}$); MS (m/z, %): 207 (M^+, 30), 192 (44), 161 (13), 146 (43), 120 (2), 106 (5), 90 (13), 43 (10), 32 (25), 28 (100).



Scheme 1. The synthesis of carbamates from CO_2 and amines.

RESULTS AND DISCUSSION

Electrocarboxylations

To optimize the experimental conditions for the electrochemical synthesis of carbamates, the influence of various parameters was checked using aniline as a model compound. Accordingly, several electrolyses were carried out using different numbers of faradays per mole of amine supplied to the electrodes (Q), different cathode materials, different temperatures, different supporting salts and amounts of catalyst.

The reaction yields were shown to be dependent on the reaction conditions, particularly on the cathodic materials. Table 1 (entries 1–5) presents the results obtained with the use of graphite as the anode, and of Cu, Ti, Ni, steel stainless or C as the cathodic materials for the electrocarboxylation of aniline. The yields were obtained under potentiostatic control and 2.5 F/mol of aniline were consumed. By comparing entries 1–5, the best cathodic material is Cu.

To investigate the effect of the temperature on the electrocarboxylation of aniline, a set of electrolyses was carried out at different temperatures (entries 6–8). According to the Arrhenius equation, the activation energy required for the electroreduction of CO_2 decreased with increasing temperature. Conversely, the solubility of CO_2 in DMF solution also declined with elevating temperature. In view of the two contradictory factors, too high or low a temperature is unfavorable to the electrocarboxylation of aniline. The result shows that the best temperature is 20 °C.

The effect of supporting electrolyte on the electrocarboxylation of aniline was also studied. With regard to the supporting electrolyte, by comparing entries 7 and 9, the nature of the anion has little impact on the yield of ethyl carbanilate; however, obvious differences could be observed between the quaternary ammonium cations and the alkali metal cations (entries 7 and 11). Saeki *et al.*[16] considered that the tetraethylammonium cation (TEA^+) played an important role in the electrochemical reduction of CO_2 in a CO_2 + DMF medium such that when the TEA salt was used as supporting electrolyte, $CO_2^{\cdot-}$ could be stabilized by forming an ion pair, $\{TEA^+—CO_2^{\cdot-}\}$, which favored electrocarboxylation of aniline, and reactions where $CO_2^{\cdot-}$ reacted with itself and CO_2

DOI: 10.1002/aoc

Table 1. Reaction of aniline with CO_2 and EtI in DMF solution under various synthetic parameters ($E = -1.6$ V, C anode)

Entry	Cathode	Supporting electrolytes	T (°C)	Q (F/mol)	Yield (%)
1	Cu	TEABr	20	2.5	55.4
2	Steel stainless	TEABr	20	2.5	40.5
3	Ni	TEABr	20	2.5	10
4	Ti	TEABr	20	2.5	52.4
5	C	TEABr	20	2.5	29.1
6	Cu	TEABr	0	1.5	40.4
7	Cu	TEABr	20	1.5	43.7
8	Cu	TEABr	40	1.5	34.4
9	Cu	TEAI	20	1.5	38.6
10	Cu	TBABr	20	1.5	41.6
11	Cu	KBr	20	1.5	24.9
12	Cu	LiCl	20	1.5	16.8
13	Cu	TEABr	20	1	32.1
14	Cu	TEABr	20	1.5	43.7
15	Cu	TEABr	20	2	49.2
16	Cu	TEABr	20	2.5	55.4
17	Cu	TEABr	20	3	60.8
18	Cu	TEABr	20	4	61.2

were avoided to some extent. However, an alkali metal cation not only cannot stabilize CO_2^{-}, but also has a strong attractive force with the aniline anion and the interaction between alkali metal cation and aniline anion is significant enough to depress the nitrogen nucleophilicity and increase the difficulty of the aniline anion reacting with CO_2.

Since the concentration of the electrogenerated CO_2^{-} in DMF-TEABr solutions is affected by the number (Q) of faradays supplied to the electrodes per mole of aniline, the yield of ethyl phenylcarbamate increases with increasing Q. Consequently, the reaction of aniline and CO_2 under various passed charges was examined (entries 13–18). Under potentiostatic control, the best passed charge was 3 F/mol. Before that point, the yields were increasing rapidly with increase in the passed charge. After that point, the yields were increasing slowly with increase in the passed charge.

Table 2 shows the effects of the catalyst on the carbonylation. By comparing entries 19–22, the amount of catalyst has little impact on the yield of ethyl phenylcarbamate and a small amount of catalyst used in the electrolysis is enough to catalyze CO_2 to give CO_2^{-}. However, the coordination of the catalyst shows a significant impact on the yield of ethyl phenylcarbamate. Electrogenerated Ni^0 or Ni^{-1} with too many negative charges will be unstable in the absence of bipyridyl (bpy), which will reduce the electron cloud density of the Ni^0 or Ni^{-1} on account of electron delocalization between Ni and bpy. Therefore, bpy plays an important role in stabilizing the electrogenerated Ni^0 and Ni^{-1} complexes. The greater the amounts of bpy, the more the electrogenerated Ni^0 and Ni^{-1} complexes will be stabilized.

Table 2. Influence of catalyst on the yield of ethyl carbanilate (Cu cathode, C anode, $Q = 2$ F/mol, $E = -1.6$ V, 20 °C)

Entry	Catalyst	Amounts of catalyst	n_{cat}/n_{phNH2}	Yield (%)
19	$Ni(bpy)_3Cl_2$	0.05 mmol	1:200	37.1
20	$Ni(bpy)_3Cl_2$	0.1 mmol	1:100	49.2
21	$Ni(bpy)_3Cl_2$	0.2 mmol	1:50	50.4
22	$Ni(bpy)_3Cl_2$	0.3 mmol	3:100	51.8
23	$Ni(bpy)Cl_2$	0.1 mmol	1:100	43.8

Table 3. Synthesis of carbamates **2** via reaction of amine **1** with electrochemically activated CO_2 in DMF-TEABr solution followed by addition of EtI ($E = -1.6$ V, Cu cathode, C anode, $Q = 3$ F/mol)

Entry	Amine	Carbamate	Yield (%)
24	**1a**	**2a**	60.8
25	**1b**	**2b**	58.5
26	**1c**	**2c**	75.6
27	**1d**	**2d**	82.2
28	**1e**	**2e**	32.7
29	**1f**	**2f**	15.8

To test the effectiveness and generality of this methodology, we extended the investigation to amines **1b–f**, carrying out the reactions under optimized conditions (see Table 1, entry 17). With all amines, carbamates were obtained. Moreover, the yields were strongly affected by the nuclephilicity of the amine (Table 3).

Cyclic voltammetry

The interaction of amines and CO_2 with $Ni(bipy)_3Cl_2$ was examined by cyclic voltammetry. Figure 1 presents the behavior of the nickel complex in a DMF solution containing tetraethylammonium bromide at room temperature. The cyclic voltammogram of a DMF–TEABr solution [Fig. 1(A)] showed that no reduction peak could be observed in sweeping the region over −0.3 to −2.2 V. After 5 mmol/l $Ni(bpy)_3Cl_2$ was added to the DMF solution, three redox waves could be found at −0.884 (1), −1.599 (2) and −1.900 V (3), respectively [Fig. 1(B)]. The first redox wave (1) should correspond to a Ni^{2+}/Ni^0 complex transition. The second redox wave (2) should correspond to a Ni^0/Ni^{-1} complex transition, according to our research on $Ni(bpy)_3Cl_2$. The third redox wave (3) should be reduction–oxidation of the free bpy ligand resulting from the dissociation of the Ni complex. In order to comfirm that the third redox wave belonged to bpy, another 1-fold molar quantity of bpy was introduced to the solution, but no obvious changes of the first and second redox currents was observed. Conversely, the redox current 3 showed a significant increase, so the third redox wave should correspond to reduction–oxidation

DOI: 10.1002/aoc

of bpy. In the presence of from 0.5 to 10 equivalents [Fig. 1(B)] of aniline, no significant changes of the curve B could be observed, which indicates that there is no strong interaction and no rapid chemical reaction between the aniline and the electrogenerated nickel complexes. Bubbling CO_2 into the solution containing $Ni(bpy)_3Cl_2$ resulted in modified cyclic voltammograms, as illustrated in Fig. 1(C). A slightly higher intensity than for curve B was seen at the first reductive wave, but the corresponding oxidative wave nearly disappeared. This oxidative current change in the presence of CO_2 can be explained via ligand exchange between the CO_2 and bpy. Most of the Ni^0 complex exists in the form of $Ni^0(bpy)(CO_2)$ in the DMF solution rather than as $Ni^0(bpy)_2$ (Fig. 2). Hence, the corresponding oxidative current will decrease sharply. The cyclic voltammogram [Fig. 1(C)] presents an irreversible Ni^{-1}/Ni^0 transition (2) at −1.598 V. In the presence of CO_2 (saturated solution at atmospheric pressure), the electrogenerated Ni^{-1} complex transfers an electron to a CO_2 group to yield $CO_2^{\cdot-}$ and Ni^0 complex, so the corresponding oxidative wave disappears. Bpy is liberated from the Ni^0 complex when CO_2 coordinates to the Ni^0 complex; hence, the concentration of bpy in the solution is higher than the one without CO_2, namely, the redox current 3 at −1.9 V increased at the same rate. Electrogenerated $CO_2^{\cdot-}$ as a strong base is able to deprotonate amine to yield amine anions, which then react with CO_2 and EtI to give organic carbamates.

CONCLUSION

In conclusion, a new electrochemical procedure for the synthesis of carbamates from amine and carbon dioxide has been established by the electroreduction of carbon dioxide in the presence of $Ni(bpy)_3Cl_2$ in a CO_2-saturated DMF–TEABr solution containing amine, followed by addition of EtI as an alkylating agent. This synthesis was carried out under mild conditions, without any addition of toxic, harmful probases. After optimization of the synthetic parameters, 3 F/mol of charge had passed through the cells at room temperature under potentiostatic control. Yields of carbamates **2a–f** were obtained from 15 to 82%, respectively. It is also worth noting that this reported method utilizing $CO_2^{\cdot-}$ as a base for the synthesis of carbamates constitutes an example in the field of green chemistry. Study of the further utility of this method is in progress.

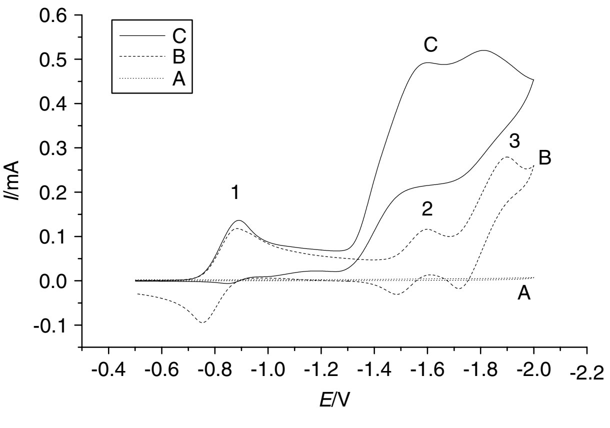


Figure 1. Cyclic voltammetry on GC electrode, at 100 mV s^{-1} and room temperature, in DMF solution with 0.1 mol/l TEABr; reference electrode Ag–AgI. (A) DMF–0.1 mol/l; TEABr; (B) after addition of 5 mmol/l $Ni(bpy)_3Cl_2$; (C) after saturation with CO_2 at 1 atm.

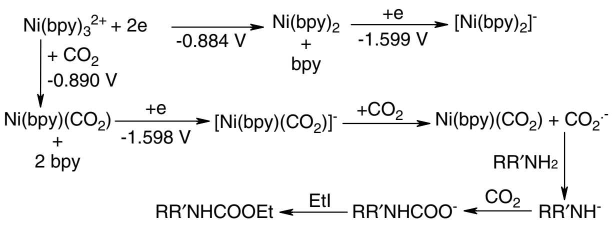


Figure 2. Reaction route in the synthesis of carbamates from CO_2 and amines.

Acknowledgment

This work was financially supported by the Natural Science Foundation of China (20573037) and Natural Science Foundation of Shanghai (05JC14070).

REFERENCES

1. Mateen A, Chapalamadugu S, Kashar B, Batthi AR, Chaudry GR. *Biol. Degrad. Biorem. Toxic. Chem.* 1994; 198.
2. Wigfiled YY. *Food Sci. Technol. (NY)* 1996; **77**: 1501.
3. Green T, Wuts PGM. *Protective Groups in Organic Synthesis*, 2nd edn. Wiley: New York, 1991; 315.
4. Adams P, Baron FA. *Chem. Rev.* 1965; **65**: 567.
5. Feroci M, Cassadei MA, Orsini M, Palombi L, Inesi A. *J. Org. Chem.* 2003; **68**: 1548.
6. Feroci M, Inesi A, Rossi L. *Tatrahedron Lett.* 2000; **41**: 963.
7. Alwis CD, Crayston JA, Cromie T, Eisenblatter T. *Electrochim. Acta* 2000; **45**: 2061.
8. Kamekawa H, Senboku H, Tokuda M. *Tetrahedron Lett.* 1998; **39**: 1591.
9. Amatore C, Saveant JM. *J. Am. Chem. Soc.* 1981; **103**: 5021.
10. Hoshi N, Hori Y. *Electrochim. Acta.* 2000; **45**: 4263.
11. Koshechkovg VG, Lopushanskaya VA. *Theor. Exp. Chem.* 2006; **42**: 33.
12. Tanaka K, Mizukawa T. *Appl. Organomet. Chem.* 2000; **14**: 863.
13. Lee J, Tak Y. *Electrochim. Acta* 2001; **46**: 3015.
14. Kaneco S, Iiba K, Yabuuchi M. *Ind. Engng Chem. Res.* 2002; **41**: 5165.
15. Zhang L, Luo YW, Niu DF, Yu XD, Lu JX. *Chin. J. Catal.* 2007; **28**: 100.
16. Saeki T, Hashimoto K, Kimura N, Omata K, Fujishima A. *J. Electroanal. Chem.* 1995; **390**: 77.