Stereospecific Electrochemical Carboxylation of β-Bromostyrene by Use of Nickel(II) Catalyst

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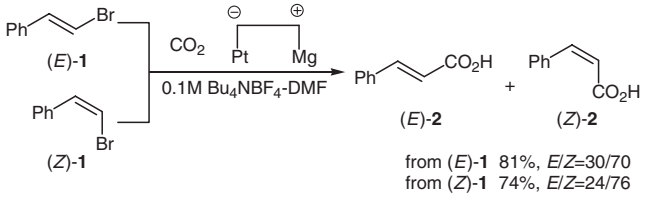
(Received January 12, 2005; CL-050056)

Electrochemical carboxylation of (*E*)- and (*Z*)-β-bromostyrenes (**1**) under an atmospheric pressure of carbon dioxide with a platinum cathode and a magnesium anode in the presence of 20 mol % of $NiBr_2$·bpy proceeded with retention of stereochemistry to give the corresponding (*E*)- or (*Z*)-cinnamic acids (**2**). The stereochemical outcome of nickel(II)-catalyzed electrochemical carboxylations was discussed by comparison with predominant formation of a (*Z*)-isomer from either (*E*)- or (*Z*)-β-bromostyrenes.

Electrochemical carboxylation is one of the most useful methods for the fixation of carbon dioxide to organic molecules because it is a clean and environmentally benign process. It takes place efficiently even in an atmospheric pressure of CO_2 under neutral and mild conditions to give carboxylic acids in high yields when a reactive-metal such as magnesium or aluminum is used as a sacrificial anode in the electrolysis.[1] We have already reported that electrochemical carboxylation of vinyl halides and vinyl triflates gave the corresponding carboxylic acids in high yields.[2] In 1996, we found that thermodynamically less-stable (*Z*)-cinnamic acids ((*Z*)-**2**) were preferentially produced from either (*E*)- or (*Z*)-β-bromostyrene ((*E*)-**1** or (*Z*)-**1**) in the electrochemical carboxylations.[3] Electrochemical carboxylation of (*E*)-**1** gave a 30/70 mixture of (*E*)-**2** and (*Z*)-**2**, whereas that of (*Z*)-**1** also gave a 24/76 mixture of (*E*)-**2** and (*Z*)-**2** (Scheme 1).



Scheme 1.

As one of our continuing studies on electrochemical carboxylation, we attempt to develop a novel route for the stereoselective electrochemical carboxylation of (*E*)-**1** and (*Z*)-**1** by use of nickel(II) catalyst. In this paper, we report our results concerning stereoselective electrochemical carboxylation and mechanistic aspects of this reaction.

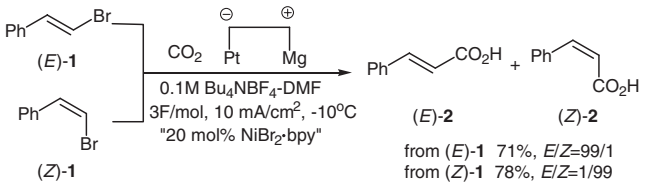
We first examined the electrochemical carboxylation of (*E*)-**1** under various conditions. The results are summarized in Table 1. Various conditions were examined to optimize the yield and stereoselectivity. It was found that electrochemical carboxylation of (*E*)-**1** in the presence of 20 mol % of nickel(II) bromide-2,2′-bipyridine complex ($NiBr_2$·bpy), at −10 °C and 5 mA/cm^2 of constant current with an electricity of 3 Faradays per mol of (*E*)-**1** gave the corresponding acid **2** ($E/Z = 99/1$) with retention of its stereochemistry in a 71% yield (Table 1, Entry 6).

Table 1. Electrochemical carboxylation of (*E*)-β-bromostyrene ((*E*)-**1**) under various conditions[a]

Entry	Catalyst $NiBr_2$·bpy	Temperature /°C	Current density /mA cm^{-2}	Electricity /F mol^{-1}	Yield /%[b]	Isomer ratio *E*/*Z*[c]
1	—	5	10	3	81	30/70
2	—	−10	10	3	61	21/79
3	10 mol %	−10	10	3	66	78/22
4	20 mol %	−10	10	3	65	88/12
5	20 mol %	−10	15	3	47	67/33
6	20 mol %	−10	5	3	71	99/1
7	20 mol %	20	10	3	72	91/9
8	20 mol %	−10	5	4.5	76	77/23

[a](*E*)-β-bromostyrene (3 mmol) in 0.1 M Bu_4NBF_4-DMF (15 mL) was electrolyzed in the presence of 20 mol % of $NiBr_2$·bpy under an atmospheric carbon dioxide with a Pt cathode and a Mg anode. [b]Isolated yields. [c]Isomer ratios were determined by ^{1}H NMR.

Similar nickel-catalyzed electrochemical carboxylation of (*Z*)-**1** under the same condition as that of (*E*)-**1** gave the corresponding acid **2** ($E/Z = 1/99$) in a 78% yield (Scheme 2).[4] The use of an aluminum or zinc anode, instead of magnesium anode, in the electrochemical carboxylation of (*E*)-**1** resulted in a decreased yield and stereochemistry of the acid **2**. Electrochemical carboxylation of (*E*)-**1** in the presence of 20 mol % of $NiBr_2$·bpy, using a platinum cathode and an aluminum anode gave a 76/24 mixture of (*E*)-**2** and (*Z*)-**2** only in a 45% yield. Additionally, electrochemical carboxylation of (*E*)-**1** using a zinc anode gave a mixture of acid **2** ($E/Z = 73/27$) in only a 9% yield. These results show that a magnesium anode plays an important role in efficient electrochemical carboxylation and its stereochemistry. It was also found that palladium catalyst such as $Pd(PPh_3)_4$, $PdCl_2(PPh_3)_2$ were not effective in this reaction.

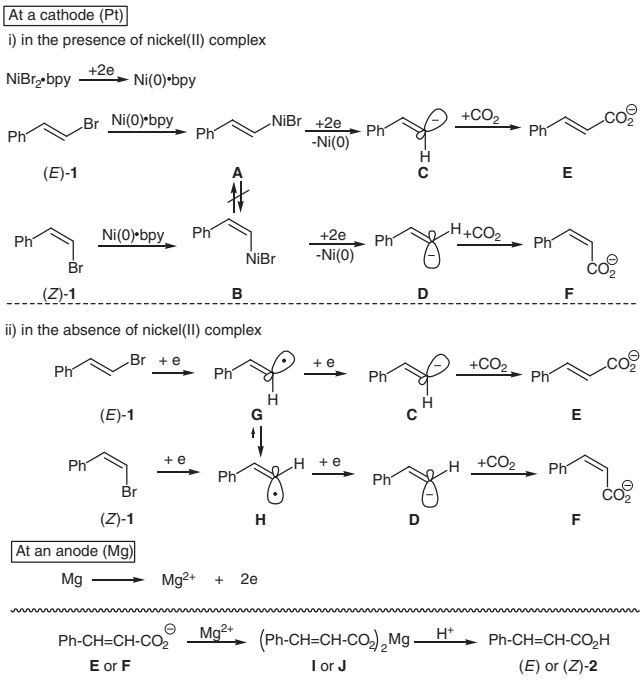


Scheme 2.

The present electrochemical method is useful for the synthesis of substituted (*E*)- or (*Z*)-cinnamic acids since the starting (*E*)- or (*Z*)-vinyl bromides can readily be prepared in high yields.[5] The electrochemical carboxylation of (*Z*)-vinyl bromides with CO_2 has especially been proposed as a useful proce-

dure for the production of (*Z*)-cinnamic acids which are difficult to prepare by conventional method,[6a] even though the conversion of (*E*)-cinnamic acids to its (*Z*)-isomer has been reported.[6b]

The probable reaction pathways of the present electrochemical carboxylation are shown in Scheme 3. At the cathode, in the presence of nickel catalyst, a two-electron reduction of $NiBr_2$•bpy gives Ni(0) species, and an oxidative addition of the Ni(0) to (*E*)- or (*Z*)-**1** would produce the intermediate **A** or **B**, isomerization could not occur between **A** and **B** at this stage. A two-electron reduction of **A** or **B** gives the corresponding vinyl carbanion (**C** or **D**), which is trapped by atmospheric carbon dioxide to give the corresponding alkenoate (**E** or **F**). At the anode, on the other hand, a dissolution of magnesium metal takes place to give magnesium ion. The magnesium ion readily captures 2-alkenoates (**E** or **F**) to give the stable magnesium carboxylate **I** or **J**. Acid treatment of **I** or **J** gives (*E*)-**2** or (*Z*)-**2**. Cyclic voltammetry of (*E*)-**1** and (*Z*)-**1** in the presence of $NiBr_2$•bpy showed the existence of an additional reduction peak at ca. −1.98 and −1.97 V vs Ag/AgCl, respectively, while the reduction peaks of (*E*)-**1**, (*Z*)-**1** and $NiBr_2$•bpy alone appeared at −2.59, −2.62, and −1.53 V, respectively.[7] These result suggest that in the presence of $NiBr_2$•bpy, a direct two-electron reduction of intermediate **A** or **B** may take place preferentially over a one-electron reduction giving an equilibration between two (*E*)- and (*Z*)-vinyl radical.



Scheme 3.

In the absence of nickel catalyst, a one-electron reduction of (*E*)- or (*Z*)-**1** gives the corresponding vinyl radical **G** or **H**, respectively (Scheme 3). In an equilibration between vinyl radicals **G** and **H**, the radical **H** would gain an advantage over radical **G** due to some interaction of a magnesium ion with a phenyl group and a radical center. When a platinum anode, instead of a magnesium anode, was used in the electrochemical carboxylation of (*E*)-**1**, (*E*)-**2** was predominantly produced. This result indicates that a magnesium ion, formed by dissolution of a magnesium anode in electrolysis, plays an important role in the (*Z*)-selectivity of electrochemical carboxylation of vinyl bromides. In order to find a further evidence of this prospect, we investigated the electrochemical carboxylation of (*Z*)-1-bromo-3-cyclohexylethylene ((*Z*)-**3**) in the absence of nickel catalyst, much to our delight, a 51/49 mixture of (*E*)- and (*Z*)-3-cyclohexylpropenoic acid ((*E*)- and (*Z*)-**4**) was obtained in a 23% yield. Because of an absence of π-electron in cyclohexyl group, stability of the two vinyl radicals is not so different, hence electrochemical carboxylation of (*Z*)-**3** gave the (*E*)- and (*Z*)-**4** in almost same ratio. These results showed that both π-electron of phenyl group and magnesium ion are essential in regulation of the stereoselectivity of electrochemical carboxylation of vinyl bromides.

In summary, we have developed a novel route for the stereoselective electrochemical carboxylation of β-bromostyrene by use of nickel(II) catalyst. The stereochemical mechanistic aspects of nickel(II)-catalyzed electrochemical carboxylations are discussed by comparison with predominant formation of a (*Z*)-isomer from either (*E*)- or (*Z*)-β-bromostyrenes.

This work was supported by a Grant-in-Aid for Scientific Research (A) (No. 07555580) from The Ministry of Education, Culture, Sports, Science and Technology, Japan.

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4 Typical procedure for the nickel(II)-catalyst electrochemical carboxylation of β-bromostyrene is described in the followings: A mixture of (*E*)-β-bromostyrene ((*E*)-**1**, 3 mmol) and $NiBr_2$•bpy (0.6 mmol) and Bu_4NBF_4 (1.5 mmol) in 15 mL of DMF was added into a one-compartment cell equipped with a platinum plate cathode ($2 \times 3\,cm^2$) and a magnesium rod anode (3 mmϕ). The mixture was electrolyzed at −10 °C at $5\,mA/cm^2$ of constant current under a slow stream of carbon dioxide gas until an electricity of 3 Faradays per mol of (*E*)-**1** was passed. The electrolyzed solution was poured into 2N HCl and extracted with diethyl ether (3×50 mL). After the organic layer was washed with water (4×50 mL), it was extracted by saturated sodium hydrogen carbonate (3×50 mL). The aqueous layer was again acidified with 2N HCl and extracted with diethyl ether (3×50 mL). The organic layer was washed with brine and dried over MgSO4. Filtration and evaporation of the solvent afforded cinnamic acid **2** ($E/Z = 99/1$) in 71% yield. Mp 133–134 °C; ^{1}H NMR (270 MHz, $CDCl_3$) δ 6.46 (1H, d, $J = 16.1$ Hz), 7.39–7.44 (3H, m), 7.52–7.57 (2H, m), 7.80 (1H, d, $J = 16.1$ Hz); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 117.30, 128.35, 128.93, 130.72, 133.98, 147.09, 172.66.

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7 Reduction peak potentials of (*E*)- and (*Z*)-β-bromostyrene and $NiBr_2$•bpy were determined by cyclic voltammetry of 2 mM substrates in 0.1 M Bu_4BF_4-DMF with a gold disk electrode (1.6 mmϕ) at the scan rate of 0.1 V/s.

Published on the web (Advance View) March 5, 2005; DOI 10.1246/cl.2005.528