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## Stereospecific Electrochemical Carboxylation of $\beta$ -Bromostyrene by Use of Nickel(II) Catalyst

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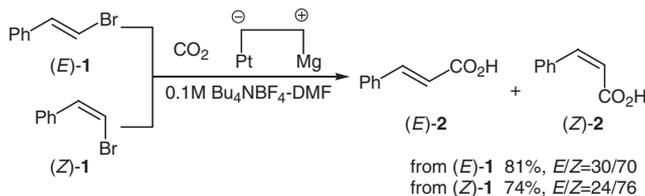
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Electrochemical carboxylation of (*E*)- and (*Z*)- $\beta$ -bromostyrenes (**1**) under an atmospheric pressure of carbon dioxide with a platinum cathode and a magnesium anode in the presence of 20 mol % of NiBr<sub>2</sub>·bpy proceeded with retention 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*)- $\beta$ -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<sub>2</sub> 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.<sup>1</sup> We have already reported that electrochemical carboxylation of vinyl halides and vinyl triflates gave the corresponding carboxylic acids in high yields.<sup>2</sup> In 1996, we found that thermodynamically less-stable (*Z*)-cinnamic acids ((*Z*)-**2**) were preferentially produced from either (*E*)- or (*Z*)- $\beta$ -bromostyrene ((*E*)-**1** or (*Z*)-**1**) in the electrochemical carboxylations.<sup>3</sup> 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<sub>2</sub>·bpy), at -10 °C and 5 mA/cm<sup>2</sup> of constant current with an electricity of 3 Faradays per mol of (*E*)-**1** gave the corresponding acid **2** (*E/Z* = 99/1)

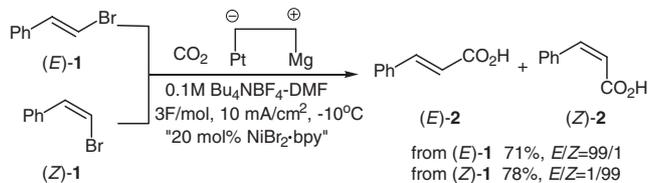
**Table 1.** Electrochemical carboxylation of (*E*)- $\beta$ -bromostyrene ((*E*)-**1**) under various conditions<sup>a</sup>

Entry	Catalyst NiBr <sub>2</sub> ·bpy	Temperature /°C	Current density /mA cm <sup>-2</sup>	Electricity /F mol <sup>-1</sup>	Yield /% <sup>b</sup>	Isomer ratio <i>E/Z</i> <sup>c</sup>
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

<sup>a</sup>(*E*)- $\beta$ -bromostyrene (3 mmol) in 0.1 M Bu<sub>4</sub>NBF<sub>4</sub>-DMF (15 mL) was electrolyzed in the presence of 20 mol % of NiBr<sub>2</sub>·bpy under an atmospheric carbon dioxide with a Pt cathode and a Mg anode. <sup>b</sup>Isolated yields. <sup>c</sup>Isomer ratios were determined by <sup>1</sup>H NMR.

with retention of its stereochemistry in a 71% yield (Table 1, Entry 6).

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).<sup>4</sup> 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<sub>2</sub>·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<sub>3</sub>)<sub>4</sub>, PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> were not effective in this reaction.

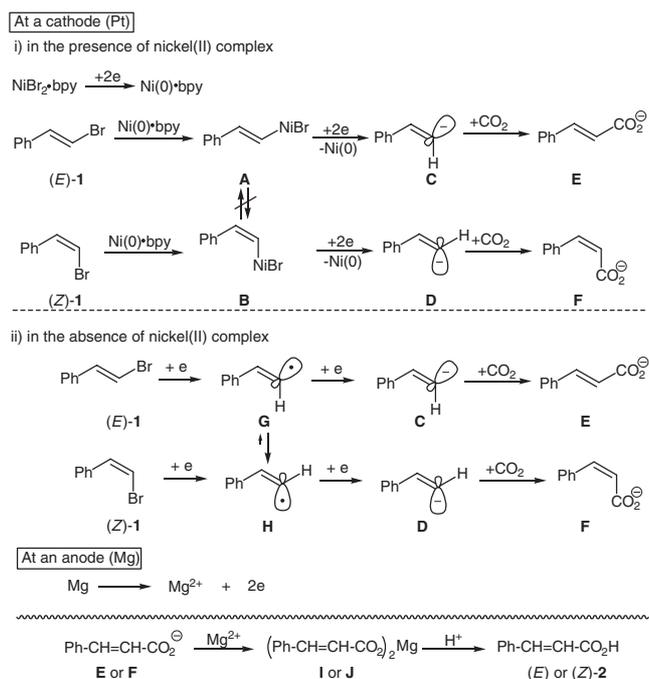


Scheme 2.

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.<sup>5</sup> The electrochemical carboxylation of (*Z*)-vinyl bromides with CO<sub>2</sub> has especially been proposed as a useful proce-

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

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<sub>2</sub>·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<sub>2</sub>·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<sub>2</sub>·bpy alone appeared at -2.59, -2.62, and -1.53 V, respectively.<sup>7</sup> These result suggest that in the presence of NiBr<sub>2</sub>·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 magne-

sium 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  $\pi$ -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  $\pi$ -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  $\beta$ -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*)- $\beta$ -bromostyrenes.

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- Typical procedure for the nickel(II)-catalyst electrochemical carboxylation of  $\beta$ -bromostyrene is described in the followings: A mixture of (*E*)- $\beta$ -bromostyrene ((*E*)-**1**, 3 mmol) and NiBr<sub>2</sub>·bpy (0.6 mmol) and Bu<sub>4</sub>NBF<sub>4</sub> (1.5 mmol) in 15 mL of DMF was added into a one-compartment cell equipped with a platinum plate cathode (2 × 3 cm<sup>2</sup>) and a magnesium rod anode (3 mm $\phi$ ). The mixture was electrolyzed at -10 °C at 5 mA/cm<sup>2</sup> 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 MgSO<sub>4</sub>. Filtration and evaporation of the solvent afforded cinnamic acid **2** (*E*/*Z* = 99/1) in 71% yield. Mp 133–134 °C; <sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>)  $\delta$  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); <sup>13</sup>C NMR (67.5 MHz, CDCl<sub>3</sub>)  $\delta$  117.30, 128.35, 128.93, 130.72, 133.98, 147.09, 172.66.
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- Reduction peak potentials of (*E*)- and (*Z*)- $\beta$ -bromostyrene and NiBr<sub>2</sub>·bpy were determined by cyclic voltammetry of 2 mM substrates in 0.1 M Bu<sub>4</sub>BF<sub>4</sub>-DMF with a gold disk electrode (1.6 mm $\phi$ ) at the scan rate of 0.1 V/s.