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## EXCHANGE RATE OF ELECTRON TRANSFER STEP OF HYDROGEN ELECTRODE REACTION AT ISOELECTRIC CONDITIONS $(\delta\varphi/\delta\mu_{\text{H}^+})_{\Gamma_{\text{H}}}=1$ IN FRUMKIN'S ELECTRODE POTENTIAL THEORY

By

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### Abstract

The reversible hydrogen electrode potential on platinum was discussed on the basis of FRUMKIN's electrode potential theory. It was found that the electrode potential in acid solutions at the isoelectric conditions  $(\delta\varphi/\delta\mu_{\text{H}^+})_{\Gamma_{\text{H}}}=1$  could be divided into two independent parts, *i.e.*, the potential due to free charges on the electrode surface and that due to adsorbed hydrogen atoms, and the former depended on  $\mu_{\text{H}^+}$  and the latter on  $\mu_{\text{H}}$ , where  $\varphi$  denoted the electrode potential,  $\mu_{\text{H}^+}$  and  $\mu_{\text{H}}$  the chemical potentials of proton in solution and adsorbed hydrogen atom H, and  $\Gamma_{\text{H}}$  the surface density of the adsorbed hydrogen atom in the sense of Gibbs thermodynamics.

Taking into consideration the functional relations of these two components of the hydrogen electrode potential, it was concluded that the exchange rate of the electron transfer step of the hydrogen evolution reaction was proportional to the square root of the activity of proton in solution.

FRUMKIN<sup>1)</sup> has developed a theory on the setting up of the electrode potential on the basis of Gibbs thermodynamics in the reversible hydrogen electrode system in which the change of the charge density on the electrode surface  $\varepsilon$  occurs through the reaction:



where H is the adsorbed hydrogen atom. In this system the electrode potential is expressed thermodynamically by the equation:

$$d\varphi = d\mu_{\text{H}^+} - d\mu_{\text{H}}, \quad (2)$$

and

$$d\varphi_{\text{r}} = -d\mu_{\text{H}}, \quad (3)$$

where  $\varphi$  and  $\varphi_{\text{r}}$  denote the electrode potentials referred respectively to the

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normal hydrogen electrode and the reversible hydrogen electrode in the same solution under the atmospheric pressure of hydrogen, and  $\mu_{\text{H}^+}$  and  $\mu_{\text{H}}$  the chemical potentials of  $\text{H}^+$  and  $\text{H}$  expressed in terms of the electric unit.

FRUMKIN's theory will first be introduced in what follows.

The quantity of adsorbed hydrogen atoms in the sense of Gibbs thermodynamics  $\Gamma_{\text{H}}$  is expressed by the equation:

$$\Gamma_{\text{H}} = A_{\text{H}} - \varepsilon, \quad (4)$$

where  $A_{\text{H}}$  is the quantity of adsorbed hydrogen atoms on the electrode surface per unit area expressed in terms of the electric unit.  $\Gamma_{\text{H}}$  shows the total charge stored on the electrode surface, inasmuch as the ionization of  $\text{H}$  results in the appearance of the negative charge on the electrode surface. The conditions in which  $\Gamma_{\text{H}}$  is kept constant are called the isoelectric conditions in FRUMKIN's theory.

In acidified neutral salt solutions in which the concentration of salt is much higher than that of acid and remains constant, the states of the system can be determined by the independent variables  $\mu_{\text{H}^+}$  and  $\mu_{\text{H}}$ . In such a system the adsorbed quantity of  $\text{H}^+$  in the sense of Gibbs thermodynamics  $\Gamma_{\text{H}^+}$  is shown to be equal to  $\varepsilon$ :

$$\Gamma_{\text{H}^+} = \varepsilon, \quad (5)$$

and a fundamental relation between  $\Gamma_{\text{H}}$  and  $\Gamma_{\text{H}^+}$  can be deduced from Gibbs adsorption equation<sup>1)</sup>:

$$(\delta\Gamma_{\text{H}}/\delta\mu_{\text{H}^+})_{\mu_{\text{H}}} = (\delta\Gamma_{\text{H}^+}/\delta\mu_{\text{H}})_{\mu_{\text{H}^+}}. \quad (6)$$

The pH-dependence of the hydrogen electrode potential at the isoelectric conditions is obtained, taking into consideration Eqs. (2), (3) and (6):

$$\begin{aligned} (\delta\varphi/\delta\mu_{\text{H}^+})_{\Gamma_{\text{H}}} &= (\delta\varphi_r/\delta\mu_{\text{H}^+})_{\Gamma_{\text{H}}} + 1, \\ &= (\delta\Gamma_{\text{H}^+}/\delta\varphi_r)_{\mu_{\text{H}^+}} / (\delta\Gamma_{\text{H}}/\delta\varphi_r)_{\mu_{\text{H}^+}} + 1, \end{aligned} \quad (7)$$

since  $\Gamma_{\text{H}}$  is a function of  $\mu_{\text{H}^+}$  and  $\mu_{\text{H}}$ .

A number of experimental results on  $(\delta\varphi/\delta\mu_{\text{H}^+})_{\Gamma_{\text{H}}}$  on metals of platinum group obtained by FRUMKIN and his school<sup>2-7)</sup> show a good coincidence with those calculated by Eq. (7) from the charging curves ( $\Gamma_{\text{H}}$ ,  $\varphi_r$ -curves)<sup>8)</sup> and the adsorption curves ( $\Gamma_{\text{H}^+}$ ,  $\varphi$ -curves).<sup>9,10)</sup> Thus it has been established by FRUMKIN and his school that the mechanism of the setting up of the hydrogen electrode potential in the reversible systems can be clarified on the basis of Gibbs thermodynamics. Furthermore they have shown that it is possible to divide the electrode potential into two parts, *i.e.*, the one due to  $A_{\text{H}}$  and the other due to  $\varepsilon$ ,<sup>12,13)</sup>

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$$d\varphi = (\delta\varphi/\delta A_H)_\varepsilon dA_H + (\delta\varphi/\delta\varepsilon)_{A_H} d\varepsilon = X dA_H + Y d\varepsilon, \quad (8)$$

where

$$X \equiv (\delta\varphi/\delta A_H)_\varepsilon, \quad Y \equiv (\delta\varphi/\delta\varepsilon)_{A_H}, \quad (9 a), (9 b)$$

The reciprocals of  $X$  and  $Y$  mean the differential capacities respectively due to  $A_H$  and  $\varepsilon$ , which can be determined experimentally from the charging and adsorption curves.<sup>14,15)</sup>

According to the experimental results of FRUMKIN school,  $(\delta\varphi/\delta\mu_{H^+})_{r_H}$  practically equals unity at potentials close to the reversible hydrogen electrode potential under the atmospheric pressure in every case of platinum group metals independent of the composition of solution. The setting up of the electrode potential at the conditions  $(\delta\varphi/\delta\mu_{H^+})_{r_H} = 1$  is of special interest, since in this case  $X dA_H$  and  $Y d\varepsilon$  are shown to be mutually independent when  $|Y| \gg |X|$ , as will be shown later, so that it may be possible in this case to find which part of potential of these two is responsible for the rate of the electron transfer step (1). The present paper is concerned with a trial to find the pH-dependence of the exchange rate of the electron transfer reaction (1) at the isoelectric conditions  $(\delta\varphi/\delta\mu_{H^+})_{r_H} = 1$  on the basis of the electrode potential theory of FRUMKIN, assuming that the rate of the electron transfer step depends only on the potential set up by free charges on the electrode surface.

It can be seen from Eq. (7) that the condition  $(\delta\varphi/\delta\mu_{H^+})_{r_H} = 1$  means the constancy of  $\varepsilon$  independent of  $\varphi_r$  or  $(\delta\Gamma_{H^+}/\delta\varphi_r)_{r_{H^+}} = 0$ , as pointed out by FRUMKIN. It follows from Eq. (6) that:

$$(\delta\Gamma_H/\delta\mu_{H^+})_{r_H} = (\delta\Gamma_{H^+}/\delta\mu_H)_{r_{H^+}} = 0, \quad (10)$$

On the other hand,  $A_H$  and  $\varepsilon$  are functions of  $\mu_H$  and  $\mu_{H^+}$ . It follows that:

$$X dA_H = X(\delta A_H/\delta\mu_H)_{r_{H^+}} d\mu_H + X(\delta A_H/\delta\mu_{H^+})_{r_H} d\mu_{H^+}, \quad (11)$$

$$Y d\varepsilon = Y(\delta\varepsilon/\delta\mu_H)_{r_{H^+}} d\mu_H + Y(\delta\varepsilon/\delta\mu_{H^+})_{r_H} d\mu_{H^+}, \quad (12)$$

From Eqs. (2) and (8), we obtain:

$$X(\delta A_H/\delta\mu_H)_{r_{H^+}} + Y(\delta\varepsilon/\delta\mu_H)_{r_{H^+}} = -1, \quad (13)$$

$$X(\delta A_H/\delta\mu_{H^+})_{r_H} + Y(\delta\varepsilon/\delta\mu_{H^+})_{r_H} = 1, \quad (14)$$

Putting Eq. (10) into Eqs. (13) and (14), and taking into consideration Eq. (4), we obtain:

$$X(\delta A_H/\delta\mu_H)_{r_{H^+}} = -1, \quad (15)$$

$$(X + Y)(\delta\varepsilon/\delta\mu_{H^+})_{r_H} = 1, \quad (16)$$

Putting Eqs. (15) and (16) into Eqs. (11) and (12), and taking into consideration Eqs. (10) and (4), we obtain:

$$XdA_H = -d\mu_H + \frac{X}{X+Y}d\mu_{H^+}, \quad (17)$$

$$Yd\varepsilon = \frac{Y}{X+Y}d\mu_{H^+}, \quad (18)$$

If we assume here that  $|Y| \gg |X|$ , as realized in the case of platinum group metals,<sup>13,15)</sup> then we have from Eqs. (17) and (18):

$$XdA_H = -d\mu_H, \quad (19)$$

$$Yd\varepsilon = d\mu_{H^+}, \quad (20)$$

It can readily be seen that the summation of Eqs. (17) and (18) or (19) and (20) satisfies the thermodynamic relation (2). Eqs. (19) and (20) show that the change of the electrode potential due to  $A_H$  depends only on  $\mu_H$  and that due to  $\varepsilon$  only on  $\mu_{H^+}$ , *i. e.*, the electrode potential can be divided into two independent parts in the case  $|Y| \gg |X|$  at the isoelectric conditions  $(\delta\varphi/\delta\mu_{H^+})_{r_H} = 1$ . Let us denote in this case  $Yd\varepsilon \equiv d\varphi_1$  and  $XdA_H \equiv d\varphi_2$ , then we have from Eqs. (19) and (20):

$$\varphi_1 = (RT/F) \ln a_{H^+} + \text{const.} \quad (21)$$

$$\varphi_2 = -(RT/F) \ln a_H + \text{const.} \quad (22)$$

and

$$\varphi = \varphi_1 + \varphi_2, \quad (23)$$

where  $a_{H^+}$  and  $a_H$  are the activities of  $H^+$  and  $H$ .

If we assume here that the rate of the electron transfer reaction  $i_1$  depends only on  $\varphi_1$  independent of  $\varphi_2$  and can be expressed by simplified FRUMKIN equation omitted  $\Psi_1$ -potential term, then the exchange rate of the reaction  $i_{10}$  can be written as:

$$i_{10} = k(a_{H^+}) \exp(-\alpha F\varphi_1/RT), \quad (24)$$

where  $k$  and  $\alpha$  are constants. Putting Eq. (21) into (24), we obtain:

$$i_{10} = \text{const} \cdot (a_{H^+})^{1-\alpha}. \quad (25)$$

It can be seen from Eq. (25) that the exchange rate of the electron transfer step is proportional to the square root of  $a_{H^+}$  when  $\alpha$  equals 1/2.

If we assume that even in the irreversible states of the hydrogen electrode reaction the electrode potential consists of two independent parts  $\varphi_1$  and  $\varphi_2$

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and the latter is expressed by Eq. (22), then  $i_1$  is expressed by FRUMKIN equation on the assumption that the rate of the electron transfer step depends only on  $\varphi_1$  independent of  $\varphi_2$ :

$$i_1 = k'_1(a_{H^+}) \exp(-\alpha F\varphi_1/RT) - k'_2 \exp(\beta F\varphi_1/RT), \quad (26)$$

where  $k'_1$  and  $k'_2$  are constants and  $\alpha + \beta = 1$ . Putting  $\varphi_1 = \varphi - \varphi_2$  into Eq. (26), we have:

$$i_1 = k'_1(a_{H^+}) \exp\{-\alpha F(\varphi - \varphi_2)/RT\} - k'_2 \exp\{\beta F(\varphi - \varphi_2)/RT\}, \quad (27)$$

Putting Eq. (22) into (27), we obtain:

$$i_1 = k''_1(a_{H^+})(a_H)^{-\alpha} \exp(-\alpha F\varphi/RT) - k''_2(a_H)^\beta \exp(\beta F\varphi/RT), \quad (28)$$

where  $k''_1$  and  $k''_2$  are constants. If we assume  $a_H$  to be proportional to  $\exp(f\theta)$  in accordance with FRUMKIN and ALADJALOVA<sup>17)</sup>, we obtain from Eq. (28):

$$i_1 = k_1(a_{H^+}) \exp(-\alpha f\theta) \exp(-\alpha F\varphi/RT) - k_2 \exp(\beta f\theta) \exp(\beta F\varphi/RT), \quad (29)$$

where  $k_1$ ,  $k_2$  and  $f$  are constants and  $\theta$  the surface coverage of adsorbed hydrogen atoms. Comparing Eq. (29) and the rate equation obtained by FRUMKIN and ALADJALOVA,<sup>17)</sup> it can be seen that both equations are identical. This fact suggests that in the case of palladium hydrogen electrode worked out by FRUMKIN and ALADJALOVA, the isoelectric condition  $(\delta\varphi/\delta\mu_{H^+})_{r_H}$  may be equal to unity and  $|Y| \gg |X|$ , and the hydrogen overvoltage may consist of two independent parts  $\varphi_1$  and  $\varphi_2$ .

FRUMKIN's electrode potential theory in the reversible systems applies extensively to the setting up of the hydrogen overvoltage in the irreversible systems, which will be discussed later with reference to the platinum hydrogen electrode in alkaline solutions.

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