July, 1986] © *1986 The Chemical Society of Japan* *Bull. Chem. Soc. Jpn.*, *59*, *2269—2272 (1986)* 2269

Measurements of Association Constants of Iodine with Cyclodextrins and with Iodide or Bromide Ion in Aqueous Medium, Based on Volatilization Rate of Iodine from Aqueous into Gaseous Phase

Isao SANEMASA,* Yuko NISHIMOTO, Akira TANAKA, and Toshio DEGUCHI
Department of Chemistry, Faculty of Science, Kumamoto University,
Kurokami 2-39-1, Kumamoto 860
(Received January 23, 1986)

Iodine molecules, which are volatile, are expelled from an aqueous medium into the gaseous phase by introducing an inert gas at a constant flow rate into the aqueous phase, and the amount of the released iodine is measured as a function of aeration time. In the presence of a nonvolatile solute which associates with molecular iodine, the releasing rate of the volatile solute is reduced with increasing degree of the association between both the solutes in the aqueous medium. The method was applied to the case of association of iodine with α-, β-, or γ-cyclodextrin; the formation constants of the three 1:1 complexes are $(1.5\pm0.1)\times10^4$, $(1.5\pm0.2)\times10^2$, and 24 ± 3 dm^3 mol^{-1}, respectively, at 25.0 °C and low ionic strengths. The complexation of iodine with iodide or bromide ion was also studied; the I_3^- and I_2Br^- formation constants are $(6.5\pm0.1)\times10^2$ and 16 ± 1 dm^3 mol^{-1}, respectively, at 25.0 °C and I=0.1(NaClO$_4$).

The complex formation of cyclodextrin (CyD) with molecular iodine in aqueous medium is well known and association constants have been measured by the spectrophotometric,[1,2] potentiometric,[3] and solubility[4] methods. There are, however, considerable disagreements among the literature values as seen in Table 1.

A simple method for measuring association constants between volatile and nonvolatile solutes in aqueous medium has been presented and successfully used to estimate 1:1 metal acetylactonate complex formation constants.[5] The method is based on the fact that a volatile solute present in an aqueous solution can readily be driven out of the aqueous phase by an inert gas stream and that the releasing rate depends on the extent to which the volatile and nonvolatile solutes associate with each other.

Here we have used the method to determine formation constants of 1:1 complexes of iodine with α-, β-, or γ-CyDs. In order to check the reliability of the estimated values, complex formation constants of iodine with iodide or bromide ion have also been determined by the same technique.

Experimental

Materials and Preparations of Sample Solutions. Solid iodine of analytical reagent grade and cyclodextrins (α-, β-, and γ-CyD from Nakarai Chemicals) of guaranteed grade were used without further purification (γ-CyD recrystallized from water was also used). An aqueous iodine solution in the order of 1×10^{-3} M (1 M=1 mol dm^{-3}), i.e., a nearly saturated solution, was prepared by adding an excess quantity of solid iodine to 1 dm^3 of 2×10^{-4} M HClO$_4$ solution and stirring in a thermostated bath at 25 °C for a few days. Suitable portions of this iodine solution were taken out successively, and one part was used to determine the I_2 concentration by titration with a 4×10^{-3} M $Na_2S_2O_3$ standard solution using starch as an indicator and the others were diluted with water to desired iodine concentrations ranging from 10^{-5} to 10^{-4} M to prepare CyD-free sample solutions. Into the aqueous iodine solution was dissolved a suitable amount of CyD, which had been dried over phosphorus pentaoxide under vacuum, to prepare sample solutions of known CyD concentrations. The HClO$_4$ concentration in the sample solution was as low as 2×10^{-6}—2×10^{-5} M.

In runs where formation constants were to be estimated for I_2–I^- and I_2–Br^- systems, sample solutions were prepared by adding a suitable volume of an iodide or bromide stock solution which had been prepared by dissolving a dried reagent (KI, NaBr) in water. The ionic strength of the sample solution was adjusted to 0.1 with NaClO$_4$.

Apparatus and Procedures. The apparatus used to expel molecular iodine was essentially the same as the one employed in a previous work.[5]

A 50 cm^3 portion of sample solution was transferred into a 2.5$\phi\times$25 cm cylindrical glass tube with a ground glass joint, which was then immersed in a bath thermostated at 25.0±0.1 °C. A gas-inlet-type adaptor was mounted on the cylindrical tube and N_2 gas was dispersed through the solution via a capillary glass tube at a constant flow rate of 60.0 cm^3 min^{-1}. The N_2 gas flow rate was controlled by a Stec Type Sec 400 mass-flow controllor, which was donated by Standard Technology Co., Ltd. (Kyoto); an accuracy within ±1% is guaranteed for this device. The N_2 gas leaving the sample solution was dispersed via a sintered glass ball through an absorbent, 20 cm^3 of 5×10^{-4} M $Na_2S_2O_3$ solution, which was placed in a 15$\phi\times$18 cm cylindrical glass tube with a ground glass joint. After a fixed time, the N_2 gas stream was interrupted, the absorption vessel was replaced by another one containing the same volume of the absorbent, and the introduction of N_2 gas was resumed. This operation was repeated at regular time intervals. The amount of iodine expelled from the sample solution during the fixed time, ΔQ_{I_2}, i.e., the amount of I_2 trapped in a single absorption vessel, was determined by measuring the discoloration degree of trisulfatocerium(IV) at 312 nm according to the flow injection analysis (FIA).

The principle of the analytical method is that the reduction of Ce(IV) by As(III) will be promoted in the presence of iodide ion as a catalyst. The FIA manifold was the same as the one previously used,[6] but the temperature of the reaction coil where the catalytic reaction occurs was set at 30 °C and the absorbent, 5×10^{-4} M $Na_2S_2O_3$, was employed as a carrier stream into which portions of a sample solution were injected. Under these conditions, we could detect iodide ions down to 1×10^{-8} M.

Results and Discussion

Formation Constants of Molecular Iodine with Cyclodextrins. The stoichiometry of α-, β-, or γ-CyD complex with molecular iodine has been established to be 1 : 1,[4,7,8] and thus the reactions that should be taken into account are

$$\mathrm{CyD} + \mathrm{I_2} \rightleftarrows \mathrm{CyD}\cdot\mathrm{I_2},\ K_{\mathrm{ass}}, \tag{1}$$

$$\mathrm{I_2(aq)} \longrightarrow \mathrm{I_2(gas)},\ k, \tag{2}$$

where K_{ass} is the association constant and k is the rate constant for expulsion of iodine molecules from the aqueous into gaseous phase. Here we assume that the iodine present in the aqueous medium is in the molecular form, that is, the hydrolysis of iodine, $I_2+H_2O \rightleftarrows HIO+H^++I^-$, is negligible, because of its small hydrolysis constant of the order of 10^{-13}.[9]

The iodine molecules expelled into the gaseous phase are trapped successively by the absorbent, and the total amount, $Q_{\mathrm{I_2}}$, is measured as a function of aeration time, t. Here, we assume that the releasing rate of I_2 at a constant N_2 gas flow rate is of first-order dependence on the concentration of this species present in the solution, and thus

$$\mathrm{d}Q_{\mathrm{I_2}}V^{-1}/\mathrm{d}t = k[\mathrm{I_2}], \tag{3}$$

where V is the volume of the aqueous phase. We have the mass-balance equations

$$C_{\mathrm{CyD}} = [\mathrm{CyD}] + [\mathrm{CyD}\cdot\mathrm{I_2}], \tag{4}$$

$$\begin{aligned} C_{\mathrm{I_2}} &= [\mathrm{I_2}] + Q_{\mathrm{I_2}}V^{-1} + [\mathrm{CyD}\cdot\mathrm{I_2}] \\ &= [\mathrm{I_2}] + Q_{\mathrm{I_2}}V^{-1} + K_{\mathrm{ass}}[\mathrm{CyD}][\mathrm{I_2}], \end{aligned} \tag{5}$$

where C_{CyD} and $C_{\mathrm{I_2}}$ are the total concentration of CyD and that of iodine, respectively. Substitution of Eq. 5 into Eq. 3 yields

$$\mathrm{d}Q_{\mathrm{I_2}}V^{-1}/\mathrm{d}t = k(C_{\mathrm{I_2}} - Q_{\mathrm{I_2}}V^{-1})/(1 + K_{\mathrm{ass}}[\mathrm{CyD}]), \tag{6}$$

which becomes, on integration and with $Q_{\mathrm{I_2}}=0$ at $t=0$,

$$\ln(C_{\mathrm{I_2}} - Q_{\mathrm{I_2}}V^{-1}) = -kt/(1 + K_{\mathrm{ass}}[\mathrm{CyD}]) + \ln C_{\mathrm{I_2}}. \tag{7}$$

Plots of $\ln(C_{\mathrm{I_2}}-Q_{\mathrm{I_2}}V^{-1})$ vs. t will give a straight line

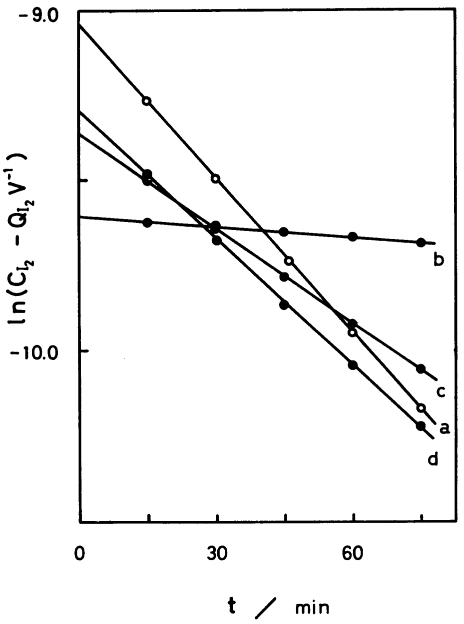

Fig. 1. The plots of $\ln(C_{\mathrm{I_2}}-Q_{\mathrm{I_2}}V^{-1})$ vs. t in the absence and presence of cyclodextrin. N_2 gas flow rate 60.0 $\mathrm{cm^3\,min^{-1}}$; (a): $C_{\mathrm{CyD}}=0$, $C_{\mathrm{I_2}}=1.18\times10^{-4}$ M, (b): $C_{\alpha\text{-CyD}}=1.00\times10^{-3}$ M, $C_{\mathrm{I_2}}=6.73\times10^{-5}$ M, (c): $C_{\beta\text{-CyD}}=5.00\times10^{-3}$ M, $C_{\mathrm{I_2}}=8.70\times10^{-5}$ M, (d): $C_{\gamma\text{-CyD}}=1.00\times10^{-2}$ M, $C_{\mathrm{I_2}}=9.20\times10^{-5}$ M.

Table 1. The α-, β-, γ-Cyclodexetrin–Iodine Association Constants at 25 °C Determined in This Work and the Literature Value

C_{CyD}[a)]/mol dm^{-3}	$C_{\mathrm{I_2}}$[b)]/mol dm^{-3}	K_{ass}[c)]/dm^3 mol^{-1}
α-Cyclodextrin		
2.50×10^{-4}	1.06×10^{-5}	1.6×10^{4}
5.01×10^{-4}	1.99×10^{-5}	1.5×10^{4}
1.00×10^{-3}	6.73×10^{-5}	1.4×10^{4}
		Average: $(1.5\pm0.1)\times10^{4}$
Literature K_{ass} Value: $(9.3\pm0.2)\times10^{3}$ d), $(2\pm1)\times10^{4}$ e), 2×10^{3} f), 8.3×10^{3} g)		
β-Cyclodextrin		
9.99×10^{-4}	4.61×10^{-5}	1.7×10^{2}
2.50×10^{-3}	2.23×10^{-5}	1.6×10^{2}
5.00×10^{-3}	8.70×10^{-5}	1.3×10^{2}
		Average: $(1.5\pm0.2)\times10^{2}$
Literature K_{ass} Value: $(1.5\pm0.5)\times10^{3}$ e), 1.0×10^{2} g), 1.85×10^{3} h)		
γ-Cyclodextrin		
5.00×10^{-3}	1.45×10^{-4}	23
9.99×10^{-3}	1.04×10^{-4}	19
9.99×10^{-3}	3.92×10^{-5}	26
5.00×10^{-3} i)	9.20×10^{-5}	28
1.00×10^{-2} i)	9.20×10^{-5}	24
		Average: 24 ± 3
Literature K_{ass} Value: $(3.5\pm0.5)\times10^{2}$ e), 13 g)		

a) Total concentration of cyclodextrin. b) Total concentration of iodine. c) Association constant determined in this work (each value is an average of two measurements obtained under the same C_{DyD} and $C_{\mathrm{I_2}}$ concentrations. d) Ref. 1. e) Ref. 3. f) Cited in Ref. 3. g) Ref. 4. h) Ref. 2. i) The cyclodextrin used was recrystallized from water.

with a slope which corresponds to $-k/(1+K_{\mathrm{ass}}[\mathrm{CyD}])$ or to $-k$ in the absence of CyD solutes. Under the conditions that the total concentration of CyD is sufficiently large compared to the concentration of the associated complex formed, that is, $C_{\mathrm{CyD}} \gg [\mathrm{CyD} \cdot \mathrm{I_2}]$, we can set [CyD] in Eq. 7 equal to C_{CyD}.

Figure 1 shows some plots constructed with the aid of Eq. 7. These plots give straight lines over the aeration time investigated, which indicates that the releasing rate of I_2 is of first-order dependence on the concentration of this species present in the solution. At a constant N_2 gas flow rate of 60.0 $\mathrm{cm^3\,min^{-1}}$, the constant, k, was evaluated to be $(1.53\pm0.03)\times10^{-2}$ $\mathrm{min^{-1}}$ (an average from four replicated runs in the absence of CyD). The association constants derived for α-, β-, and γ-CyD complexes with iodine from the negative slopes of the straight lines are tabulated together with C_{CyD} and $C_{\mathrm{I_2}}$ in Table 1, where those reported so far in the literature are also listed.

With α-CyD, the cavity size of which is 4.7—5.2 Å, an iodine molecule can suitably be fitted with a van der Waals contact.[8] On the other hand, β- and γ-CyDs provide much less stable complexes with the guest owing to their large cavity sizes, 6.0—6.4 and 7.5—8.3 Å, respectively.

The association constants obtained by the present method are about 1.5 to 2 times as large as our previous ones[4] determined through solubility measurements. The disagreement, however, may be taken as rather small if we take it into consideration that quite different techniques were employed for the two works. The K_{ass} value determined in this work for the α-CyD complex is in reasonable agreement with that recently reported by Diard et al.[3] as a result of potentiometric measurements, while the values for β- and γ-complexes differ by one order of magnitude; their association constants decrease every one order of magnitude on going from α- to γ-CyD, while our values display a difference as much as two orders of magnitude between α- and β-CyD complexes.

It probably admits of no argument that the α-complex has the association constant as large as $1\times10^4\,\mathrm{M^{-1}}$. The association constant for β- and γ-complexes, on the other hand, are still far from being generally acceptable. This is partially attributable to their relatively small association constants; the spectrophotometric, potentiometric, and solubility measurements are all desirable to be done under high CyD concentrations to get reliable values, β-CyD has a limited solubility in water (ca. 10^{-2} M). In view of its small association constant, some impurities which may be present in γ-CyD might cause serious errors in the estimatin of K_{ass} of γ-CyD–I_2. There is observed, however, no appreciable difference between the results obtained from purified (recrystallized from water) and untreated γ-CyD specimens, as can be seen from Table 1.

In order to make it clear whether the present method provides reasonable association constants as small as 10^2 or 10, I_2–I^- and I_2–Br^- systems were studied. The formation constant for the former system has been measured by many investigators and the latter is known for its small formation constant.

Formation Constants of Molecular Iodine with Iodide or Bromide Ion. The reactions that should be taken into account are

$$X^- + I_2 \rightleftharpoons I_2X^-,\ K_{\mathrm{I_2X}}, \tag{8}$$

$$I_2(\mathrm{aq}) \longrightarrow I_2(\mathrm{gas}),\ k, \tag{2}$$

where X^- denotes either I^- or Br^- and $K_{\mathrm{I_2X}}$ is the formation constant. An equation that allows estimation of the formation constant of I_2 with I^- or Br^- can be derived in the same way as described in the CyD–I_2 system:

$$\ln(C_{\mathrm{I_2}} - Q_{\mathrm{I_2}}V^{-1}) = -kt/(1 + K_{\mathrm{I_2X}}[X^-]) + \ln C_{\mathrm{I_2}}. \tag{9}$$

Experiments having been made under the condition that the total concentration of X^-, C_X, is sufficiently large compared to the concentration of the complex formed, we can set $[X^-]$ in Eq. 9 equal to C_X. Some examples of plots obtained with the aid of Eq. 9 are shown in Fig. 2. The plots also give straight lines

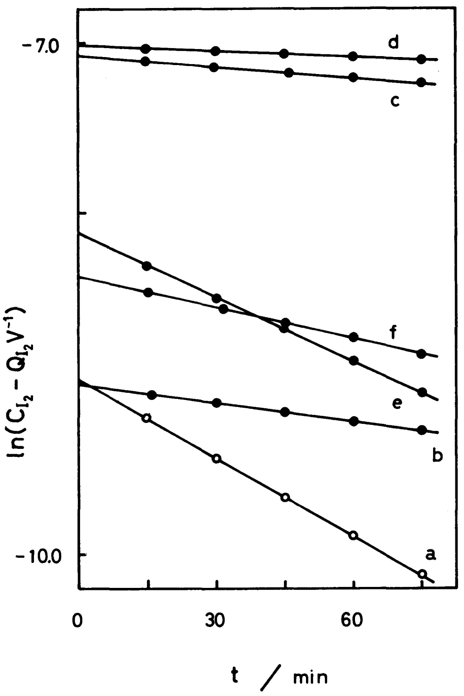

Fig. 2. The plots of $\ln(C_{\mathrm{I_2}}-Q_{\mathrm{I_2}}V^{-1})$ vs. t in the absence and presence of I^- or Br^-. N_2 gas flow rate 60.0 $\mathrm{cm^3\,min^{-1}}$; (a): $C_X=0$, $C_{\mathrm{I_2}}=1.27\times10^{-4}$ M, (b): $C_{\mathrm{I}}=5.00\times10^{-3}$ M, $C_{\mathrm{I_2}}=1.23\times10^{-4}$ M, (c): $C_{\mathrm{I}}=1.00\times10^{-2}$ M, $C_{\mathrm{I_2}}=8.37\times10^{-4}$ M, (d) $C_{\mathrm{I}}=2.00\times10^{-2}$ M, $C_{\mathrm{I_2}}=9.01\times10^{-4}$ M, (e): $C_{\mathrm{Br}}=2.00\times10^{-2}$ M, $C_{\mathrm{I_2}}=2.96\times10^{-4}$ M, (f): $C_{\mathrm{Br}}=1.00\times10^{-1}$ M, $C_{\mathrm{I_2}}=2.31\times10^{-4}$ M.

Table 2. I_3^- and I_2Br^- Formation Constants Determined at 25 °C and I=0.1($NaClO_4$)

C_X[a)] mol dm^{-3}	C_{I_2}[b)] mol dm^{-3}	K_{I_2X}[c)] dm^3 mol^{-1}
$I^- + I_2 \rightleftharpoons I_3^-$		
2.50×10^{-3}	1.20×10^{-4}	6.4×10^2
2.50×10^{-3}	1.26×10^{-4}	6.5×10^2
5.00×10^{-3}	1.23×10^{-4}	6.6×10^2
1.00×10^{-2}	8.37×10^{-4}	6.4×10^2
1.25×10^{-2}	1.25×10^{-4}	6.6×10^2
2.00×10^{-2}	9.01×10^{-4}	6.3×10^2
	Average:	$(6.5\pm0.1)\times10^2$
$Br^- + I_2 \rightleftharpoons I_2Br^-$		
5.00×10^{-2}	2.91×10^{-4}	15
1.00×10^{-1}[d)]	2.31×10^{-4}	16
	Average:	16±1

a) Total concentration of halide ion. b) Total concentration of iodine. c) Formation constant. d) $NaClO_4$ was not added; I=0.1(NaBr).

over the aeration time investigated. Formation constants calculated from the slopes of the straight lines for I_3^- and I_2Br^- by using the k value 1.54×10^{-2} min^{-1} determined with 0.1 M $NaClO_4$ are listed in Table 2, together with C_{I_2} and C_X.

To our knowledge, only three K_{I_2Br} values have been reported; 14.9 M^{-1} by spectrophotometry,[10)] 12.2 M^{-1} from solubility,[11)] and 8.35 M^{-1} through solvent extraction.[12)] The present result, 16 M^{-1}, is in reasonable agreement with the first one cited; because of the lack of available literature values, it is difficult at present to judge whether the agreement is accidental or not.

With respect to K_{I_3}, on the other hand, abundant literature data are available which have been obtained by spectrophotometric,[13,14)] potentiometric,[9,15)] distribution,[12,16)] solubility,[17,18)] and conductimetric[19)] methods. Some representative values are arranged in decreasing order of magnitude as follows: 768,[16)] 761,[17)] 7.3×10^2,[14)] 725,[9)] 723,[13)] 714,[15)] 680,[12)] and 654[17)] M^{-1}. If we choose 723 M^{-1} as the most reliable K_{I_3} value in accord with the recommendation by Ramette and Sandford,[20)] the present result, 6.5×10^2 M^{-1}, is about 10% lower. As has been pointed out by many investigators, the I_3^- formation constant should be determined under as low iodine and/or iodide concentrations as possible. The observed K_{I_3} tends to increase with increasing iodine and/or iodide concentrations due to significant formation of higher polyiodide species such as I_5^- and I_6^{2-} in addition to I_3^-.[16,20)] From this point of view, the present method, which employs very low I_2 and I^- concentrations, seems to provide rather a small I_3^- formation constant.

After all, the method proposed here can be used to determine association constants with molecular iodine, magnitudes of which are as small as the order of 10^2 or 10.

The present work was partially supported by a Grant-in Aid for Scientific Research No. 6054037 from the Ministry of Education, Science and Calture.

References

1) J. A. Thoma and D. French, *J. Phys. Chem.*, **62**, 1603 (1958).
2) Y. Miyazaki, *Saga Daigaku Nogaku Iho*, **31**, 49 (1971).
3) J. P. Diard, E. Saint-Aman, and D. Serve, *J. Electroanal. Chem. Interfacial Electrochem.*, **189**, 113 (1985).
4) I. Sanemasa, T. Kobayashi, and T. Deguchi, *Bull. Chem. Soc. Jpn.*, **58**. 1033 (1985).
5) I. Sanemasa, Y. Nishimoto, A. Tanaka, and T. Deguchi, *Bull. Chem. Soc. Jpn.*, **59**, 1459 (1986).
6) T. Deguchi, A. Tanaka, I. Sanemasa, and H. Nagai, *Bunseki Kagaku*, **32**, 23 (1983).
7) J. A. Thoma and D. French, *J. Am. Chem. Soc.*, **80**, 6142 (1958).
8) R. K. McMullan, W. Saenger, J. Fayos, and D. Mootz, *Carbohydr. Res.*, **31**, 37 (1973).
9) J. D. Burger and H. A. Liebhafsky, *Anal. Chem.*, **45**, 600 (1973).
10) Daniele, *Gazz. Chim. Ital.*, **90**, 1082 (1960).
11) V. K. LaMer and M. H. Lewinsohn, *J. Phys. Chem.*, **38**, 171 (1934).
12) L. S. Sowers and S. A. Katz, *Rev. Latinoamer. Quim.*, **5**, 80 (1974): *Chem. Abstr.*, **81**, 54951b (1974).
13) G. Daniele, *Gazz. Chim. Ital.*, **90**, 1068 (1960).
14) K. Hayakawa and S. Nakamura, *Bull. Chem. Soc. Jpn.*, **50**, 566 (1977).
15) G. Jones and B. B. Kaplan, *J. Am. Chem. Soc.*, **50**, 1845 (1928).
16) M. Davies and E. Gwynne, *J. Am. Chem. Soc.*, **74**, 2748 (1952).
17) L. I. Katzin and E. Gebert, *J. Am. Chem. Soc.*, **77**, 5814 (1955).
18) J. S. Carter, *J. Chem. Soc.*, **130**, 2227 (1928).
19) W. C. Bray and C. M. MacKay, *J. Am. Chem. Soc.*, **32**, 914 (1910).
20) R. W. Ramette and R. W. Sandford, Jr., *J. Am. Chem. Soc.*, **87**, 5001 (1965).