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INCLUSION OF FERROCENECARBOXYLIC ACID AND ITS CARBOXYLATE ANION BY β-CYCLODEXTRIN AS OBSERVED BY INDUCED CIRCULAR DICHROISM

Nagao KOBAYASHI and Tetsuo OSA
Pharmaceutical Institute, Tohoku University, Aobayama, Sendai 980

Induced circular dichroism (i.c.d.) has revealed that the arrangements of ferrocenecarboxylic acid (FCA) and its carboxylate anion (FCA^-) in β-cyclodextrin (β-CDx) are significantly different from each other. Based on the previously accummulated knowledge on i.c.d., the orientation of FCA and FCA^- in β-CDx is conjectured to be different by almost 90 degree in the X-Z plane, provided that the positions of these species in β-CDx cavity are the same.

It is believed, from the consideration using Corey-Pauling-Koltun (CPK) molecular models, that ferrocene has just a suitable size for the inclusion by β-CDx.1) In the course of studies, however, we noticed fortuitously that the i.c.d. spectra of FCA in the presence of β-CDx in aqueous solutions at pH 1 (0.05 M (1 M = 1 mol dm^{-3}) H_2SO_4) and 9 (calcium carbonate saturated 0.05 M Na_2CO_3) were completely different from each other. Although the analysis of i.c.d. of CDx-chromophore host-guest complexes has provided the information on the orientation,2) chirality,3) and so on4) of guest molecules, no report has appeared to date that confirms a significant change of arrangement of guest molecules in CDxs. We present here the evidence that the arrangement of a guest molecule in cyclodextrin can be altered dramatically only by a slight change in the guest-structure quoting FCA as an instance, i.e. by dissociation of its carboxyl group.

Figure 1 shows the i.c.d. spectra of FCA in the presence of β-CDx in aqueous solutions at pH 1 and 9 and in ethylene glycol. The sign of the i.c.d. at pH 9 was all negative in 208-550 nm while, on the contrary, that at pH 1 was positive except only in 450-550 nm region. Besides, the positions of many i.c.d. peaks and troughs are almost consistent with those of absorption peaks and shoulders. These i.c.d. spectra at pH 1 and 9 were reversibly observable by the change of pH value. Compared with such a drastic change in the i.c.d., the absorption spectra at pH 1 and 9 did not differ significantly to each other, suggesting that the effect of dissociation of the carboxyl group on the electronic structure of FCA is not marked. The stoichiometry of FCA-β-CDx inclusion complex was 1:1 at both pH 1 and 9, as indicated clearly by the continuous variation plots in Fig. 2.

Concerning the i.c.d. of CDx-chromophore 1:1 inclusion complexes, the followings have been substantiated or shown on the basis of Kirkwood-Tinoco coupled oscillator expression.5) (i) The electronic transitions parallel to the molecular axis of CDxs produce positive i.c.d., while those normal to the axis show negative i.c.d.2d,f) This was confirmed experimentally using in particular compounds which have clear long- and short-axes polarized transitions such as mono-, *p*-di-substituted

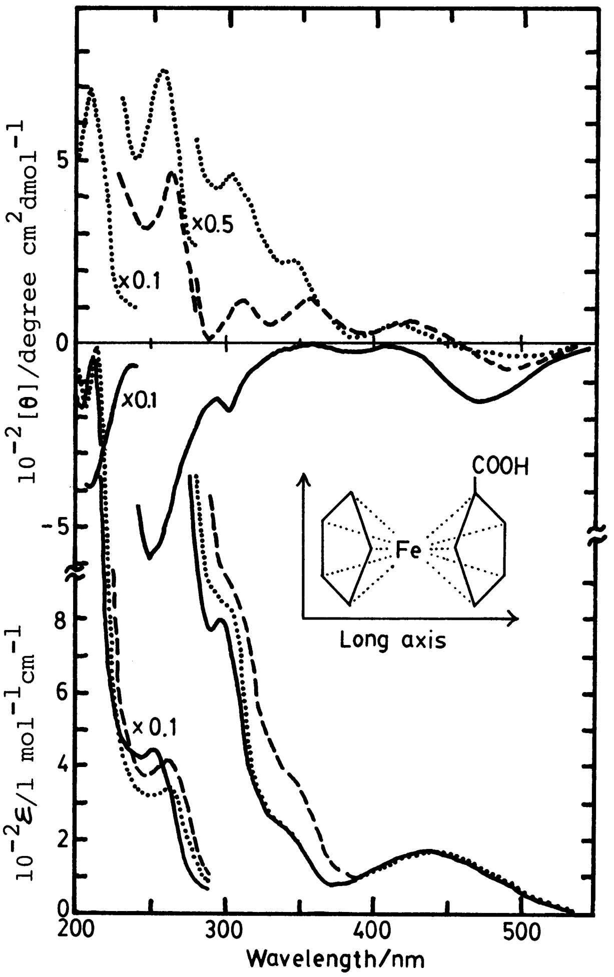

Fig. 1. The UV-visible absorption and i.c.d. spectra of FCA in water at pH 1 (······) and 9 (——) and in ethylene glycol (– – –). [FCA]/M = 4.41 x 10^{-4}, 1.0 x 10^{-3}, and 4.06 x 10^{-3} in water at pH 1 and 9 and in ethylene glycol, respectively. [β-CDx] /M = 1.0 x 10^{-2} in water and 1.0 x 10^{-1} in ethylene glycol. (Cells of pathlengths of 0.2, 1, 5, 10, and 20 mm were used.)

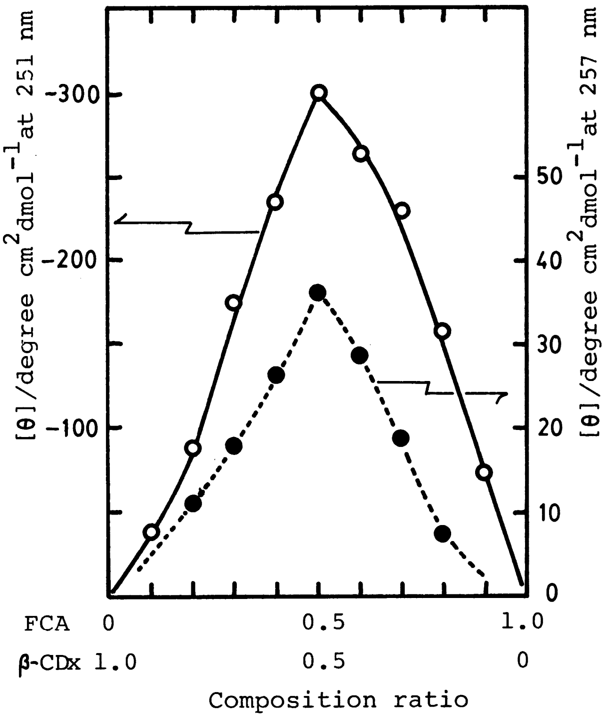

Fig. 2. The continuous variation plots for FCA-β-CDx system at pH 1 (dotted line, 257 nm) and pH 9 (solid line, 251 nm). Conditions of the experiments: i) at pH 1; [FCA]/M = [β-CDx]/M = 4.41 x 10^{-4}. Cells of pathlengths of 10 and 20 mm were used. ii) at pH 9; [FCA]/M = [β-CDx]/M = 2.5 x 10^{-3}. Pathlengths of cells used were 5, 2, and 1 mm. Complex formation constants between FCA and β-CDx evaluated from the i.c.d. intensity change were 235 M^{-1} and 483 M^{-1} at pH 1 and 9, respectively (Benesi-Hildebrand method$^{9)}$).

benzenes,$^{2f)}$ and pyrene.$^{2g)}$ (ii) The sign of the calculated rotational strength does not change by the translations of the guest molecules along X-, Y-, and Z-axis, though their magnitudes are affected$^{2f)}$ (the origin of axes is in the center of CDx and Z-axis is parallel to the molecular axis of CDx). (iii) The rotation of the guest molecule in the X-Y plane has no influence on the calculated rotational strength, while that in the X-Z plane does have a great influence on it.$^{2f)}$ Accordingly, if the assignment of absorption bands and the directions of the electric dipole moments are known, we can estimate the orientation of the chromophore molecules accommodated in the cavity of CDxs based on (i). The assignment of the bands of FCA and ferrocene derivatives has been attempted by many researchers and those at the 320-550 nm region

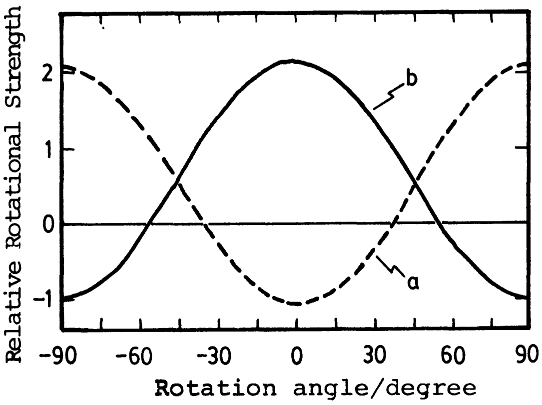

Fig. 3. The dependence of the calculated rotational strengths of a CDx-chromophore complex on the rotation angle in the X-Z plane. Curves a and b are for the transitions along normal and parallel to the molecular axis of the CDx, respectively.

have been assigned to d-d transitions of iron(II).6) Further, the absorption peak around 440 nm has been proposed to contain two components with absorption maxima at 420-430 and 460-470 nm, the latter arising from a d-d transition with little contribution from the cyclopentadienyl (Cp) system. An intense band at 210-220 nm had previously been assigned to a relatively pure π-π^* transition in the Cp rings,6a) though another possibility was shown later.6b) The interpretation on other regions is also not consistent among researchers. Thus it appears difficult to deduce the orientation of FCA and FCA$^-$ in β-CDx. However, if we dare accept the assignment that the band at 210-220 nm is due to a π-π^* transition, the corresponding positive i.c.d. at pH 1 (Fig. 1) supports an equatorial inclusion of FCA molecule (note that this inclusion is equivalent to an axial inclusion of Cp rings). Also, since the signs of i.c.d. spectra at pH 1 and 9 are different, the difference in inclusion at pH 1 and 9 is not expressed merely as a difference of position of FCA in β-CDx cavity by the criterion (ii). Then, it is inferred, based on (iii), that the difference at pH 1 and 9 is expressed mainly as a difference of the angle between the molecular axis of β-CDx and the Z-axis of FCA (Φ_1) or FCA$^-$ (Φ_2), i.e. $\Phi_1-\Phi_2$ ($\equiv\Phi$). Using the Kirkwood-Tinoco coupled oscillator model,5) the dependence of calculated rotational strength on the rotation of the electric transition moment in the X-Z plane is presented as depicted in Fig. 3. This figure indicates, as shown for example by curve a, that the transitions polarized normal to the molecular axis of CDx (negative in i.c.d. sign) can produce positive i.c.d. sign when the guest molecules are rotated more than ca. ±36 degree, and especially that the i.c.d. intensity become approximately the double of the first value when the guests are rotated 90 degree. We can, therefore, estimate the Φ using this figure on the assumption that the position of FCA in β-CDx cavity does not change at pH 1 and 9 (this assumption is concerned with the latter part of (ii)). So, in order to utilize Fig. 3, the observed i.c.d. curves were fit by three Gaussian lines in the 200-350 nm region (not shown, the wavelengths of the center of respective curves were put at around the wavelengths of i.c.d. peaks or troughs). By the change of pH value from 9 to 1, together with the conversion of i.c.d. sign, the magnitude (area) increased by about 2.1 and 1.9 times in the around 200-240 and 240-280 nm regions, respectively. Moreover, if the difference in complex formation constants, i.e. the difference in [FCA] and [FCA$^-$] accommodated in β-CDx is taken into account, the values become even larger. Thus, the value of Φ appears to be close to almost 90 degree. Hence, if we suppose an equatorial inclusion at pH 1, the inclusion at pH 9 would be close to an axial inclusion (if the band at 210-220 nm is a charge-transfer band between Cp rings and iron(II),6b) then the opposite result is obtained, i.e. the inclusion at pH 1 is an axial inclusion, while that at pH 9 would be close to an equatorial inclusion). Considering the interdistance of Cp rings in ferrocene (3.3 Å)[7] and the size of the wider entrance of β-CDx cavity (ca. 8 Å, the CPK model), not only an axial inclusion but also the inclusion close to an equatorial inclusion are possible. On top of these, X-ray studies have indicated that ferrocene is relatively a round molecule, with the H atoms displaced toward Fe atom.[7,8] This may account for the facile alternaton of orientation of FCA in β-CDx cavity due to the slight change in circumstances (change of pH in this case).

In conclusion, we have shown that the arrangement of FCA in β-CDx changes dramatically by the dissociation of its carboxyl group. Based on the knowledge on i.c.d., the orientation of FCA and FCA$^-$ in β-CDx was inferred to be different by almost 90 degree in the X-Z plane, provided that the positions of these species in β-CDx cavity are the same. Judging from the spectra in Fig. 1, the inclusion of FCA in ethylene glycol appears to be close to that in water at pH 1.

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