Chapter 2

Dependence of Selective Enclathration on Types of Cholic Acid Crystals

2.1 Introduction

There have been growing interests in separation engineering using a crystallization process due to its high efficiency, cost performance, energy saving, less wasted products, and simple procedure. In particular, this process has an advantage in separating organic chemicals that are heat sensitive and decompose at temperatures required for distillation. However, target compounds are required to form crystalline mass by themselves. This has restricted versatile use of the crystallization as separation process for organic compounds. Recently, this difficulty has been partly solved by use of inclusion crystals that are crystalline molecular complexes. In the inclusion compounds, host compounds construct the open frameworks with void space and liquid guest compounds are included in the host cavities. For instance, urea is known to form urea adducts with appropriate solutes, and this urea adduction method has been employed in separating n-paraffins. Recently, Hassan and coworkers studied the adsorption of n-paraffins on solid urea rather than into urea crystals to improve the separation. As another intriguing example, Toda and coworkers demonstrated the ability of separation and optical resolution of many hosts, including brucine, sparteine, bis-β-naphthol, tartarate derivatives, acetylenic alcohols, and alkylammonium halide. Ward and coworkers reported the separations of aromatic compounds using molecular sandwiches based on guanidinium disulfonates. However, it is still difficult to design the host-guest compounds that display effective separation of guest mixtures. More recently, much attention has been paid for the rationalization of selective enclathrations on the basis of crystal structures and isomerism of open host frameworks.

Cholic acid (CA), one of the bile acids, was found to form inclusion crystals with various organic compounds. The crystal structures and guest versatility have been investigated, and the separation of mixtures of aniline and nitrobenzene by CA has been ever reported. More
recently, our systematic investigations of CA inclusion crystals with mono-substituted benzenes revealed that CA forms four different host frameworks dependent on the size and shape of the aromatic guest compounds. This motivates us to investigate the relationship between the host framework types and the selectivity among mono-substituted benzenes that have enough molecular size to afford stable inclusion compounds. In this report, we demonstrate the competitive recrystallizations of CA from aromatic compounds and reveal what factors dominate the selectivity in such system using X-ray crystallography.

![Molecular structure of n-alkylbenzenes](image)

\[ R = H : \text{benzene} \]
\[ R = \text{CH}_3 : \text{toluene} \]
\[ R = \text{CH}_2\text{CH}_3 : \text{ethylbenzene} \]
\[ R = (\text{CH}_2)\text{CH}_3 : \text{propylbenzene} \]
\[ R = (\text{CH}_2)_2\text{CH}_3 : \text{butylbenzene} \]
\[ R = (\text{CH}_2)_3\text{CH}_3 : \text{amylbenzene} \]
\[ R = (\text{CH}_2)_4\text{CH}_3 : \text{hexylbenzene} \]

Molecular structures of \(n\)-alkylbenzenes

2-2. Experimental

**Procedure for competitive recrystallization**

All chemicals and solvents were of the commercially available purest grades and used without purification. A host solution was prepared by dissolving CA (130 mg) in 1-butanol (0.4 ml), while prescribed amounts (1 mmol) of two guest compounds were mixed to make a guest solution. After mixing both solutions in a 13 ml vial, the resulting feed solution was allowed to settle overnight at 20 °C to attain crystallization equilibrium. Inclusion crystals thus obtained, in which the solvent (1-butanol) was confirmed not to be included, were filtered out and settled for some time to remove the adhering solvent and the guests on the crystal surface. Amounts of the
guests incorporated within the crystal were determined in a gas chromatograph (HP 5890SeriesII) with MS detector (HP 5971Series) after dissolving the crystal in methanol.

**Determination of single-crystal structure by X-ray crystallography**

X-ray diffractions were collected by Rigaku RAPID imaging plate two-dimensional area detector using graphite-monochromatized Cu-Kα radiation (λ=1.54178). All the crystallographic calculations were performed by using TEXSAN software package of the Molecular Structure Corporation. Each crystal structure was solved by the direct methods (SIR-92), and refined by the full-matrix least squares. All non-hydrogen atoms were refined anisotropically. Hydrogen atoms attached to carbon atoms were located in the calculated positions.

**Determination of crystal structures by powder X-ray diffraction**

The host framework types of the inclusion crystals obtained from binary mixtures were determined by X-ray powder diffraction (Rigaku RINT) at room temperature. Diffraction patterns of 2θ(˚) angle with relative intensity in parenthesis are as follows.

**Entry 1 (benzene+toluene): 6.46(13), 7.04(100), 7.50(72), 12.54(24), 12.88(20), 13.24(26), 15.10(85)**

**Entry 2 (benzene+ethylbenzene): 6.84(54), 7.02(100), 7.52(46), 12.58(15), 13.04(21), 13.30(27), 15.14(90)**

**Entry 3 (benzene+propylbenzene): 6.74(13), 7.02(100), 7.24(19), 7.44(63), 12.44(9), 12.94(11), 13.26(18), 14.52(11), 15.12(98)**

**Entry 4 (benzene+butylbenzene): 7.12(55), 7.62(43), 12.58(11), 13.02(10), 13.42(12), 15.26(100)**

**Entry 5 (benzene+amylbenzene): 6.92(31), 7.44(75), 12.46(11), 12.84(8), 13.22(22), 15.08(100)**

**Entry 6 (benzene+hexylbenzene): 6.96(10), 7.52(53), 12.56(8), 12.94(5), 13.32(10), 15.14(100)**

**Entry 7 (toluene+ethylbenzene): 6.92(52), 7.48(60), 11.04(10), 12.38(23), 12.58(26), 12.92(42), 13.24(69), 15.06(100), 15.34(57)**

**Entry 8 (toluene+propylbenzene): 6.90(13), 7.46(47), 11.02(8), 12.34(15), 12.52(19), 12.86(26), 13.14(31), 13.44(29), 15.06(100), 15.30(49)**

**Entry 9 (toluene+butylbenzene): 6.98(33), 7.50(46), 12.68(6), 12.88(8), 13.28(6), 15.12(100)**
Entry 10 (toluene+amylbenzene): 6.82(14), 6.98(19), 7.56(29), 12.68(16), 12.98(14), 13.32(17), 15.14(100)
Entry 11 (toluene+hexylbenzene): 6.86(27), 7.42(32), 12.42(12), 12.54(13), 12.84(13), 13.18(21), 15.04(100)
Entry 12 (ethylbenzene+propylbenzene): 5.80(16), 7.72(100), 10.96(9), 11.16(14), 12.92(8), 13.60(39), 14.42(22), 15.44(94), 15.84(33)
Entry 13 (ethylbenzene+butylbenzene): 6.50(7), 7.00(30), 8.22(30), 12.66(12), 12.92(62), 13.20(13), 13.84(55), 16.52(100)
Entry 14 (ethylbenzene+amylbenzene): 7.30(31), 10.26(81), 11.74(45), 12.78(30), 14.84(100), 15.66(22)
Entry 15 (ethylbenzene+hexylbenzene): 6.62(10), 6.90(39), 7.42(47), 10.24(13), 11.64(11), 12.42(18), 12.74(21), 13.06(18), 15.02(100)
Entry 16 (propylbenzene+butylbenzene): 6.98(18), 7.70(3), 7.92(4), 8.16(31), 10.82(4), 12.92(45), 13.76(13), 15.96(3), 16.44(100)
Entry 17 (propylbenzene+amylbenzene): 6.94(58), 7.48(33), 12.52(18), 12.86(12), 13.14(15), 13.44(34), 15.12(100)
Entry 18 (propylbenzene+hexylbenzene): 6.92(33), 7.50(27), 12.60(9), 12.80(6), 13.32(6), 15.10(100)
Entry 19 (butylbenzene+amylbenzene): 7.10(100), 7.62(27), 12.66(21), 12.98(13), 13.28(10), 13.56(30), 15.24(87)
Entry 20 (butylbenzene+hexylbenzene): 6.92(100), 7.46(25), 12.50(16), 12.84(7), 13.10(6), 13.38(13), 15.08(57)
Entry 21 (amylbenzene+hexylbenzene): 7.08(56), 7.64(38), 12.62(12), 13.00(12), 13.50(12), 15.22(100)

Molecular graphics and calculations

Cross sections of host channels were depicted by using MODRASTE. The atomic radii of hydrogen and carbon in the cross-sectional views are 1.20 Å and 1.60 Å, respectively.

\( PC_{cavity} \) was calculated from the volumes of the host cavity and the guest molecule. The volumes of the host cavities were calculated from the atomic coordinations by using Free
Volume program in Cerius² (version 4.0) software package.¹⁰ The atomic radii were adopted as following values: hydrogen=1.20Å, carbon=1.70Å, and oxygen=1.60Å.

2-3. Results and Discussion

Competitive recrystallizations

Inclusion compounds of CA with mono-substituted benzenes were obtained easily using 1-butanol as a solvent.⁷ The experiments described here were carried out from the guest mixtures under the guest-rich condition, i.e. crystallization was attained from solutions containing excess amounts of the two guests. Separation factor (S.F.) was defined and simplified under the present condition that the molar concentration of each guest was the same and much higher than that of the host, as follows:

\[
S.F. = \frac{([A]_{\text{cry}} / [A]_{\text{sol}})}{([B]_{\text{cry}} / [B]_{\text{sol}})} = \frac{[A]_{\text{cry}}}{[B]_{\text{cry}}}
\]

where the subscripts cry and sol denote the crystal and solution phases, respectively.

Competitive recrystallization was carried out using equimolar mixtures of n-alkylbenzenes from benzene to n-hexylbenzene, as shown in Table 2-1. The separation factors for all the binary systems of benzene and a series of n-alkylbenzenes were more than unity, indicating that benzene is preferentially incorporated in the CA crystals. The selectivity increased with increasing the number of the methylene chains in guest molecules and the separation factor reached as high as 7.6 against butylbenzene, and then the further increase deteriorated the separation factors. A similar trend can be seen in the mixtures of toluene, and the highest separation factor of 15.1 was obtained from that of toluene and propylbenzene. Moreover, guest amylbenzene and hexylbenzene are favorably included in CA compared to the other three (ethylbenzene, propylbenzene, and butylbenzene). The following combinations gave no or less selective enclathrations (0.75<S.F.<1.5); benzene + toluene, ethylbenzene + propylbenzene, ethylbenzene + butylbenzene, and amylbenzene + hexylbenzene (entry 1, 12, 13, and 21). As the results, the order of the preference to be included in CA is as follows:

benzene, toluene > amylbenzene, hexylbenzene > ethylbenzene, propylbenzene, and butylbenzene
Table 2-1  Competitive recrystallizations of CA

<table>
<thead>
<tr>
<th>Entry</th>
<th>Guest A (Host framework, host:guest ratio)</th>
<th>Guest B (Host framework, host:guest ratio)</th>
<th>$\frac{[A]<em>{\text{cry}}}{[A]</em>{\text{cry}}+[B]_{\text{cry}}} (%)$</th>
<th>$\frac{[B]<em>{\text{cry}}}{[A]</em>{\text{cry}}+[B]_{\text{cry}}} (%)$</th>
<th>S.F.</th>
<th>Host framework from 1:1 mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>benzene (α-gauche, 1:1)</td>
<td>toluene (α-gauche, 1:1)</td>
<td>54</td>
<td>46</td>
<td>1.2</td>
<td>α-gauche</td>
</tr>
<tr>
<td>2</td>
<td>benzene (α-gauche, 1:1)</td>
<td>ethylbenzene (β-trans, 1:1)</td>
<td>81</td>
<td>19</td>
<td>4.3</td>
<td>α-gauche</td>
</tr>
<tr>
<td>3</td>
<td>benzene (α-gauche, 1:1)</td>
<td>propylbenzene (β-trans, 1:1)</td>
<td>84</td>
<td>16</td>
<td>5.3</td>
<td>α-gauche + β-trans α-gauche</td>
</tr>
<tr>
<td>4</td>
<td>benzene (α-gauche, 1:1)</td>
<td>butylbenzene (α-trans, 2:1)</td>
<td>88</td>
<td>12</td>
<td>7.6</td>
<td>α-gauche</td>
</tr>
<tr>
<td>5</td>
<td>benzene (α-gauche, 1:1)</td>
<td>amylbenzene (α-gauche, 2:1)</td>
<td>80</td>
<td>20</td>
<td>4.0</td>
<td>α-gauche</td>
</tr>
<tr>
<td>6</td>
<td>benzene (α-gauche, 1:1)</td>
<td>hexylbenzene (α-gauche, 2:1)</td>
<td>72</td>
<td>28</td>
<td>2.6</td>
<td>α-gauche</td>
</tr>
<tr>
<td>7</td>
<td>toluene (α-gauche, 1:1)</td>
<td>ethylbenzene (β-trans, 1:1)</td>
<td>81</td>
<td>19</td>
<td>4.4</td>
<td>α-gauche</td>
</tr>
<tr>
<td>8</td>
<td>toluene (α-gauche, 1:1)</td>
<td>propylbenzene (β-trans, 1:1)</td>
<td>94</td>
<td>6</td>
<td>15.1</td>
<td>α-gauche</td>
</tr>
<tr>
<td>9</td>
<td>toluene (α-gauche, 1:1)</td>
<td>butylbenzene (α-trans, 2:1)</td>
<td>91</td>
<td>9</td>
<td>9.6</td>
<td>α-gauche</td>
</tr>
<tr>
<td>10</td>
<td>toluene (α-gauche, 1:1)</td>
<td>amylbenzene (α-gauche, 2:1)</td>
<td>82</td>
<td>18</td>
<td>4.7</td>
<td>α-gauche</td>
</tr>
<tr>
<td>11</td>
<td>toluene (α-gauche, 1:1)</td>
<td>hexylbenzene (α-gauche, 2:1)</td>
<td>78</td>
<td>22</td>
<td>3.5</td>
<td>α-gauche</td>
</tr>
<tr>
<td>12</td>
<td>ethylbenzene (β-trans, 1:1)</td>
<td>propylbenzene (β-trans, 1:1)</td>
<td>59</td>
<td>41</td>
<td>1.4</td>
<td>β-trans</td>
</tr>
<tr>
<td>13</td>
<td>ethylbenzene (β-trans, 1:1)</td>
<td>butylbenzene (α-trans, 2:1)</td>
<td>48</td>
<td>52</td>
<td>0.91</td>
<td>α-trans</td>
</tr>
<tr>
<td>14</td>
<td>ethylbenzene (β-trans, 1:1)</td>
<td>amylbenzene (α-gauche, 2:1)</td>
<td>32</td>
<td>68</td>
<td>0.48</td>
<td>α-gauche</td>
</tr>
<tr>
<td>15</td>
<td>ethylbenzene (β-trans, 1:1)</td>
<td>hexylbenzene (α-gauche, 2:1)</td>
<td>43</td>
<td>57</td>
<td>0.75</td>
<td>α-gauche</td>
</tr>
<tr>
<td>16</td>
<td>propylbenzene (β-trans, 1:1)</td>
<td>butylbenzene (α-trans, 2:1)</td>
<td>30</td>
<td>70</td>
<td>0.43</td>
<td>α-trans</td>
</tr>
<tr>
<td>17</td>
<td>propylbenzene (β-trans, 1:1)</td>
<td>amylbenzene (α-gauche, 2:1)</td>
<td>13</td>
<td>87</td>
<td>0.15</td>
<td>α-gauche</td>
</tr>
<tr>
<td>18</td>
<td>propylbenzene (β-trans, 1:1)</td>
<td>hexylbenzene (α-gauche, 2:1)</td>
<td>14</td>
<td>86</td>
<td>0.16</td>
<td>α-gauche</td>
</tr>
<tr>
<td>19</td>
<td>butylbenzene (α-trans, 2:1)</td>
<td>amylbenzene (α-gauche, 2:1)</td>
<td>26</td>
<td>74</td>
<td>0.35</td>
<td>α-gauche + α-trans α-gauche</td>
</tr>
<tr>
<td>20</td>
<td>butylbenzene (α-trans, 2:1)</td>
<td>hexylbenzene (α-gauche, 2:1)</td>
<td>33</td>
<td>67</td>
<td>0.50</td>
<td>α-gauche</td>
</tr>
<tr>
<td>21</td>
<td>amylbenzene (α-gauche, 2:1)</td>
<td>hexylbenzene (α-gauche, 2:1)</td>
<td>55</td>
<td>45</td>
<td>1.1</td>
<td>α-gauche</td>
</tr>
</tbody>
</table>

* Host framework and host:guest ratio means those of crystals obtained from each pure guest.
Figure 2-1. Crystal structures of CA with (a) benzene, (b) toluene, (c) ethylbenzene, (d) propylbenzene, (e) butylbenzene, (f) amylbenzene, and (g) hexylbenzene, respectively. The figures are viewed down along the crystallographic $b$-axis. Hydrogen atoms are omitted for clarity. Carbon and oxygen atoms are represented by open and filled circle, respectively.
Crystal structures of CA clathrates with $n$-alkylbenzenes

In order to clarify the guest selectivities in the competitive recrystallizations, we investigated the crystal structures of CA clathrates including the pure guest compounds, as shown in Figure 2-1. Table 2-2 summaries the lattice parameters, the types of the host frameworks, the host-guest molar ratios, and $PC_{cavity}$. They all have bilayer structure composed of hydrophilic and lipophilic layers and the guest molecules are incorporated into the one-dimensional cavity in the lipophilic layer. The structures are classified into three types of the host frameworks, $\alpha$-gauche, $\alpha$-trans, and $\beta$-trans, based on the difference in interdigitation manners of methyl groups in the lipophilic faces ($\alpha$ and $\beta$ types) and in steroidal side chain conformations ($gauche$ and $trans$ types). Benzene, toluene, amylbenzene, and hexylbenzene are included in the $\alpha$-gauche type. The others ethylbenzene and propylbenzene give the $\beta$-trans type. However, in the case of butylbenzene, the orientation of the guest compounds in the host cavity could not be confirmed because of the disorder of the phenyl ring, while the host framework is found to be the $\alpha$-trans type. Small guest molecules (benzene, toluene, ethylbenzene, and propylbenzene) are included at 1:1 host-guest ratios, and guests with carbon more than C9 (butylbenzene, amylbenzene, and hexylbenzene) are incorporated at 2:1. Namely, CA inclusion crystals with seven mono-substituted benzenes are classified into the four types, 1:1 $\alpha$-gauche, 1:1 $\beta$-trans, 2:1 $\alpha$-gauche, and 2:1 $\alpha$-trans, based on the host framework and host-guest ratio. In addition, we calculated $PC_{cavity}$, the volume ratio of the guest molecules to the host cavities, to estimate the size complementary in each crystal. The value was in the range of 52-70 %, indicating that all the aromatic guests have enough molecular size to afford stable inclusion compounds.

Elucidation of selectivities

The selectivities for the guest compounds by the enclathrations seem to be dependent on the four types mentioned above. The preference order is reviewed as below;

1:1 $\alpha$-gauche $> 2:1 \alpha$-gauche $> 1:1 \beta$-trans or 2:1 $\alpha$-trans

This order indicates that $\alpha$-gauche type host framework is more favorable than the other two trans-type ($\beta$-trans or $\alpha$-trans), and 1:1 $\alpha$-gauche type is more favorable than 2:1 $\alpha$-gauche. In addition, this order agrees with the fact that less selective enclathrations (entry 1, 12, and 21)
were observed when they construct the same host frameworks at the same host-guest ratios in a single system. For example, both benzene and toluene can be included in the same 1:1 $\alpha$-gauche type. In the same way, less selective enclathration were also observed in the cases of ethylbenzene vs propylbenzene (1:1 $\beta$-trans) and amylbenzene vs hexylbenzene (2:1 $\alpha$-gauche).

Table 2-2  Lattice parameters, host framework type, host:guest ratio, and $PCcavity$ for inclusion compounds of CA.

<table>
<thead>
<tr>
<th>Guest</th>
<th>Space group</th>
<th>$a$ (Å)</th>
<th>$b$ (Å)</th>
<th>$c$ (Å)</th>
<th>$\beta$ (°)</th>
<th>$V$ (Å$^3$)</th>
<th>Host framework</th>
<th>host:guest ratio</th>
<th>$PCcavity$ (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>benzene</td>
<td>$P2_1$</td>
<td>13.63</td>
<td>8.04</td>
<td>14.08</td>
<td>114.3</td>
<td>1406</td>
<td>$\alpha$-gauche</td>
<td>1:1</td>
<td>56</td>
<td>7</td>
</tr>
<tr>
<td>toluene</td>
<td>$P2_1$</td>
<td>13.74</td>
<td>8.04</td>
<td>14.01</td>
<td>114.1</td>
<td>1421</td>
<td>$\alpha$-gauche</td>
<td>1:1</td>
<td>60</td>
<td>7</td>
</tr>
<tr>
<td>ethylbenzene</td>
<td>$P2_1$</td>
<td>12.41</td>
<td>7.83</td>
<td>16.28</td>
<td>111.8</td>
<td>1469</td>
<td>$\beta$-trans</td>
<td>1:1</td>
<td>61</td>
<td>7</td>
</tr>
<tr>
<td>propylbenzene</td>
<td>$P2_1$</td>
<td>12.07</td>
<td>7.84</td>
<td>16.25</td>
<td>109.8</td>
<td>1447</td>
<td>$\beta$-trans</td>
<td>1:1</td>
<td>70</td>
<td>7</td>
</tr>
<tr>
<td>butylbenzene</td>
<td>$P2_1$</td>
<td>12.78</td>
<td>7.90</td>
<td>14.12</td>
<td>105.5</td>
<td>1375</td>
<td>$\alpha$-trans</td>
<td>2:1</td>
<td>52</td>
<td>this work</td>
</tr>
<tr>
<td>amylbenzene</td>
<td>$P2_1$</td>
<td>14.11</td>
<td>7.87</td>
<td>25.13</td>
<td>96.8</td>
<td>2774</td>
<td>$\alpha$-gauche</td>
<td>2:1</td>
<td>54</td>
<td>this work</td>
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<tr>
<td>hexylbenzene</td>
<td>$P2_1$</td>
<td>14.07</td>
<td>7.91</td>
<td>25.12</td>
<td>96.7</td>
<td>2779</td>
<td>$\alpha$-gauche</td>
<td>2:1</td>
<td>60</td>
<td>this work</td>
</tr>
</tbody>
</table>

Next, the host frameworks of the resulting crystals obtained from competitive experiments were determined by powder X-ray diffraction, as shown in Table 2-1. All the resulting crystals have either one of the host frameworks ($\alpha$-gauche, $\alpha$-trans, and $\beta$-trans) or their combinations. When both of the guest compounds are included in the same host framework (entries 1, 5, 6, 10, 11, 12, and 21), the competitive recrystallizations provide the same host frameworks. On the other hand, when they are included in the different host frameworks, the resulting inclusion crystals are two types of the mixtures; one is a homogenous crystal with the mixed guests in the host cavity (entries 2, 4, 7-9, 13-18, and 20) and the other is the mixture of two different inclusion crystals (entry 3 and 19). In the former, the host frameworks are the same as those from the predominant guests, and in the latter the guests are incorporated into each host framework identical to those from pure state. When one of the guest compounds in the guest mixtures gives $\alpha$-gauche host framework in pure state (entry 2, 4, 7-9, 14, 15, 17, 18, and 20), $\alpha$-gauche host framework forms exclusively and both the guests are
incorporated into the host cavity. This suggests that α-gauche type is preferred to α-trans and β-trans. In the other two cases (entry 13 and 16), only α-trans type host framework is obtained, indicating that α-trans is more preferable to β-trans.

In order to clarify the factors of the selective inclusions, we compared $PC_{cavity}$, which represents packing efficiency of the guest compounds in the host cavities, that is, size complementary. The order of $PC_{cavity}$ (propylbenzene > toluene, ethylbenzene, hexylbenzene > benzene, butylbenzene, amylbenzene) has no correlations with that of the selectivities, indicating that $PC_{cavity}$ is not suitable for the explanation of the guest selectivities. It would be due to enough packing of the guest compounds in the host cavities. As the results, the shape complementary would play an important role. Figure 2-2 illustrates typical cross-sections of the host cavities sliced parallel to the axis of the one-dimensional host cavity at the height that shows the cross-sections surrounded by the side chains. The host cavity of the α-gauche type has a square groove accommodating phenyl ring of the guest molecule (Figure 2-2 (a), (d)), while those of the trans type frameworks have triangle ones (Figure 2-2 (b), (c)). These figures illustrate that α-gauche type have host cavities should be more appropriate for phenyl ring than α-trans and β-trans type. As the results, α-gauche type predominantly forms from the guest mixtures. The host-guest ratios also play an important role for the shape fitting. In the case of the α-gauche type framework, the guest compounds that give the inclusion crystals at the 1:1 ratios are included more efficiently than those at 2:1. In the former, every square groove of the host cavities along the two-fold screw axis is occupied by the phenyl ring of the guest compounds, but in the latter one half of them are accommodated by the alkyl group. The shape complementary between a groove and guest molecule would cause the dependence of the selectivity on the four types of CA crystals.

2.4 Conclusion

We demonstrated the competitive recrystallizations of CA from 1:1 binary mixtures among seven mono-substituted benzenes that afford inclusion compounds by recrystallizations from pure liquids. The order of the preference to be included in CA crystals is as follows: benzene, toluene > amylbenzene, hexylbenzene > ethylbenzene, propylbenzene, butylbenzene which is attributed to the dominant formation of α-gauche host framework at 1:1 host-guest ratio among
Figure 2-2. Cross sections of the host channels sliced parallel to the direction of the channel (carbon and hydrogen atoms are represented by gray and white, respectively) with arrays of included guest molecules (hydrogen atoms are omitted for clarity, and carbon atom is represented by open circle); (a) toluene, (b) propylbenzene, (c) butylbenzene, and (d) hexylbenzene.

the four host frameworks. This can be understood from the suitable fitting of the phenyl ring of the guest molecule to a square groove of $\alpha$-gauche host framework. Finally, we want to emphasize here that CA exhibits shape-selective recognitions of the aromatic guests that has the enough molecular size to give stable inclusion compounds. Since CA can form inclusion compounds with a variety of organic compounds by forming diverse host frameworks with changing host-guest ratios, CA can be used for molecular recognitions of the various guest compounds. We now investigate the competitive recrystallization extensively using CA.