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Selective cyclization of 6-aminocaproic acid adsorbed on silica gel to ε-caprolactam: IR analysis of adsorbed state

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ABSTRACT: When 6-aminocaproic acid (6-ACA) was adsorbed on silica gel and the suspension of the adsorbed sample was treated in refluxing toluene, 6-ACA was selectively converted to ε-caprolactam (ε-CL) in the absence of catalysts. The relationship between adsorption of 6-ACA and its reactivity to give ε-CL was investigated by IR spectrometry with the diffuse reflection technique. The smaller the amount of 6-ACA adsorbed on silica gel, the higher both the yield and selectivity for ε-CL became. When the loading amount of 6-ACA on silica gel was lower than $\theta = 0.043$ (θ = surface coverage), the amounts of chemical species having NH_2, and C═O groups increased and a high selectivity for ε-CL was obtained. When the loading amount was higher than $\theta = 0.40$, 6-ACA was adsorbed as an amphoteric ion having NH_3^+ and CO_2^- groups as in the solid state and gave a low yield and selectivity for ε-CL. Thus 6-ACA activated by adsorption, which concomitantly hinders intermolecular interactions by suppressing the translational movement, facilitated intramolecular dehydration to yield ε-CL. Copyright © 2000 John Wiley & Sons, Ltd.

KEYWORDS: 6-aminocaproic acid; adsorption; silica gel; ε-caprolactam; IR analysis; adsorbed state

INTRODUCTION

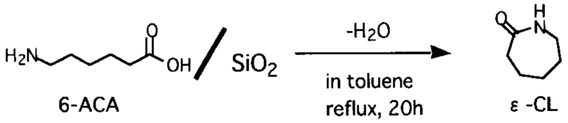
The utilization of adsorbents such as alumina and silica gel affords new routes to selective organic synthesis,[1–3] where substrates are adsorbed and oriented on the surface of adsorbents with suppression of translational movement or changes of the nature of the functional groups. Such methods have the advantages of milder reaction conditions, simpler work-up and often higher selectivity. Examples of recent studies include cyclodehydration of 15-hydroxypentadecanoic acid to ω-lactone on dealuminated H-Y zeolite,[4] selective bromination of a linear alkene in the presence of a branched or cyclic alkene on ZSM-5,[5] reduction of unsaturated ketones and aldehydes to ally1 alcohols by $Zn(BH_4)_2$ on silica gel,[6] monoacylation of α,ω-diols catalyzed by $M_x(SO_4)_y$ (M = Al, Ce, Na and Ti) on silica gel[7] and oxidation of 1,4- and 1,5-diols to lactones by sodium bromite trihydrate on alumina.[8] We have previously reported selective monomethyl esterification of longer chain dicarboxylic acids in the presence of shorter ones co-adsorbed on alumina.[9] We also reported the selective monomethyl esterification of terephthalic acid on alumina[10] and the adsorbed state of the terephthalic acid.[11] Adsorbents such as zeolite, silica gel and alumina have been used deliberately as the medium for surface reactions.

When 6-aminocaproic acid (6-ACA) or glycine was adsorbed on silica gel and then the suspension of the adsorbed sample was treated in refluxing toluene, ε-caprolactam (ε-CL)[12] or glycylglycine[13] was obtained selectively, whereas polymeric products were preferentially formed in a conventional homogeneous reaction in DMF. The relationship between adsorption and selectivity is not yet clear. This paper reports the details of the selective cyclodehydration of 6-ACA on silica gel (Scheme 1) and the relationship between the adsorption and reactivity of 6-ACA.

RESULTS AND DISCUSSION

Selective dehydration of 6-ACA to ε-CL on silica gel

An adsorbed sample was prepared by addition of silica gel to an aqueous solution of 6-ACA followed by evaporation of the water. A suspension of the adsorbed sample was refluxed in toluene and then the sample was



Scheme 1

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Table 1. Selective cyclodehydration of 6-ACA to ε-CL on SiO_2[a]

Entry	Method	Loading (θ) (10^{-4} mol g^{-1} SiO_2)	Recovered 6-ACA(%)	Yield of ε-CL(%)	Selectivity (%)
1	Adsorption[c]	0.46(0.012)	10.2	89.6	99.8
2	Adsorption[c]	3.8(0.095)	0.0	74.9	74.9
3	Adsorption[c]	26.0(0.65)	28.2	3.1	4.3
4	Adsorption[cd]	0.46(0.012)	26.0	68.3	92.3
5	Addition[e]	0.10(0.0025)[f]	3.1	44.7	46.1
6	Homogenous[g]		35.2	22.8	35.2

[a] Reactions were carried out under reflux for 20 h in toluene for adsorption methods.
[b] The value of [(yield of ε-CL)/(100 − recovered 6-ACA)] × 100.
[c] Pre-adsorbed sample of 6-ACA was used.
[d] 9.0 wt% of water was added to the adsorption sample.
[e] Silica gel (10.0 g) was added to a DMF solution (120 ml) of 6-ACA (13.1 mg).
[f] The loading amount (τ) if all the 6-ACA is adsorbed.
[g] 1.08×10^{-3} mol l^{-1} solution of 6-ACA in DMF.

extracted with solvent followed by chromatographic analysis. The results of the experiments are given in Table 1. According to this adsorption method, the product ε-CL was obtained selectively in high yield without employing catalysts. Table 1 also shows that the lower the amount of 6-ACA loaded on the silica gel the higher was the selectivity for ε-CL. 6-ACA was quantitatively recovered from the adsorbed sample when it was not refluxed in toluene. Using the conventional method in homogeneous solution using a Dean–Stark water trap, ε-CL was obtained in only 23% yield with concomitant formation of polymeric products (Table 1, entry 6). In the homogeneous reaction in DMF solution, addition of silica gel did not yield high selectivity (entry 5). The appearance of the selectivity is attributable to the surface reaction on the silica gel under heating. This method was moderately insensitive to water: the selectivity was not much affected even with the addition of water to the adsorbed sample followed by treatment in the same way (entry 4).

Zeolite has been proved to be an effective adsorbent for this method. When the adsorbed sample was prepared with the use of zeolite (F-9, Wako Chemicals; faujasite type, pore size ca 1.0 nm) containing 7.9×10^{-6} mol of 6-ACA per gram of zeolite and then treated in the same manner, ε-CL was obtained in 99% yield with 99% selectivity.

IR spectrum of 6-ACA adsorbed on silica gel

The IR spectrum of 6-ACA adsorbed on silica gel and the related spectra were measured and are illustrated in Fig. 1. The spectrum of authentic 6-ACA in the solid state exhibited the characteristic bands at 1560 cm^{-1} due to the stretching vibration of carboxylate anion [$\nu_{as}CO_2^-$ (as = asymmetric vibration)] and at 2700–2000 cm^{-1} due to the multiple combination bands of νNH_3^+ being the most prominent band near 2200 cm^{-1} [Fig. 1(b)]. The spectrum of 6-ACA adsorbed on silica gel [Fig. 1(a)] is also complicated, but it clearly shows the appearance of new bands at 1655 cm^{-1} due to the $\nu C{=}O$ stretching vibration and at 3460–3296 cm^{-1} due to the νNH_2 stretching vibration. Information about the hydroxyl group of 6-ACA could hardly be obtained because the OH group is masked by the hydroxyl group of the silica gel surface (a broad absorption at about 3500 cm^{-1}).

Some other information concerning the assignment of

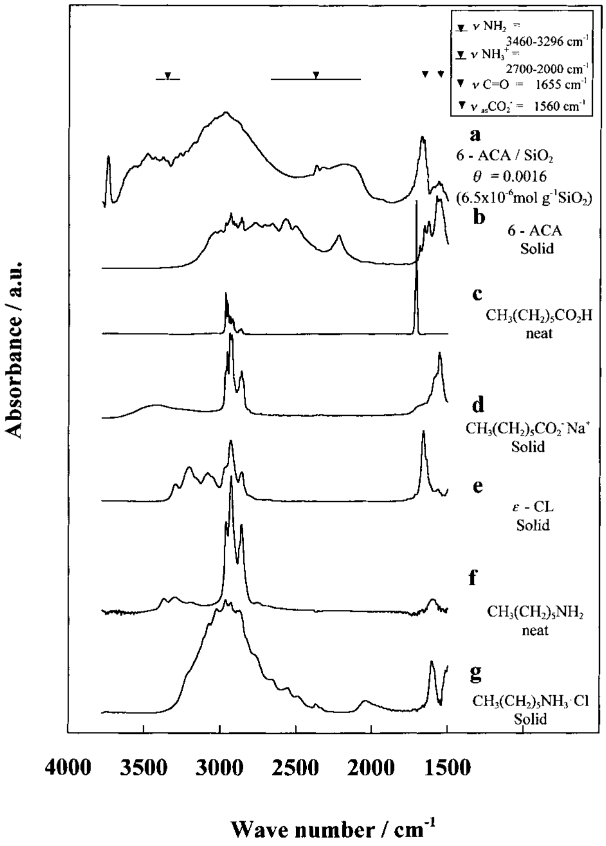


Figure 1. IR spectrum of 6-ACA adsorbed on silica gel and the related spectra. Spectrum (a) shows that 6-ACA is adsorbed on silica gel mainly as C=O and NH_2

characteristic bands was obtained as follows.[14,15] The characteristic bands of νC=O of heptanoic acid, which forms acid dimer in the neat solid, appears at 1715 cm^{-1} [Fig. 1(c)] and those of ε-CL at 1658 cm^{-1} [Fig. 1(e)]. Sodium heptanoate [Fig. 1(d)] shows the carboxylate anion CO_2^- at 1560 cm^{-1} due to $\nu_{as}CO_2^-$, which also observed in the spectrum of terephthalic acid on alumina.[11] The primary amino group of hexylamine [Fig. 1(f)] displays two absorption bands for the NH_2, stretching vibration by hydrogen bonding in the region 3460–3296 cm^{-1}, one at 3370 cm^{-1} due to $\nu_{as}NH_2$ and the other at 3296 cm^{-1} due to ν_sNH_2 (s = symmetric vibration). The spectrum also shows a weak absorption band due to bending (scissoring) vibration, δNH_2 at 1601 cm^{-1}. ε-CL in the solid state showed a strong absorption band at 3206 cm^{-1} due to νNH. Hexylammonium chloride [Fig. 1(g)] shows a broad strong stretching band near 3096 cm^{-1} arising from asymmetric and symmetrical stretching vibration of the NH_3^+ group. Multiple combination bands of medium intensity appear in the 2700–2000 cm^{-1} region with the most prominent being the band near 2046 cm^{-1}.

Both of the IR absorption bands of the carboxyl and amino groups of adsorbed 6-ACA do not match those mentioned above, suggesting the formation of different states. Consequently, when 6-ACA is adsorbed on silica gel, CO_2^- and NH_3^+ groups change to C=O and NH_2 groups, respectively. The C=O group corresponds to the carboxylic acid monomer, COOH, but the OH group cannot be measured.

Effect of loading amount

The amount of saturated adsorption of 6-ACA on silica gel was estimated by the analysis of adsorption isotherm. As shown in Fig. 2, the isotherm follows Langmuir-type adsorption and reaches saturation when the concentration of 6-ACA is higher than 10.0 mmol l^{-1}. The amount of saturated adsorption (E_∞) is 4.0×10^{-3} mol g^{-1} SiO_2 with the adsorption constant K = 123 l mol^{-1} at 25.0 °C.

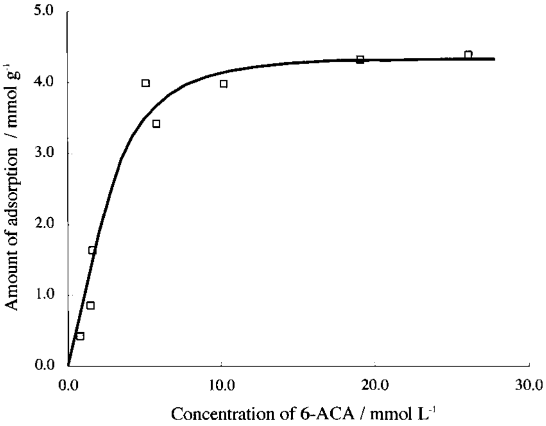


Figure 2. Adsorption isotherm of 6-ACA on silica gel in methanol at 25.0 °C. This isotherm shows Langmuir-type adsorption: saturation amount $E_\infty = 4.0 \times 10^{-3}$ mol g^{-1} SiO_2 with adsorption constant K = 123 l mol^{-1}

The IR absorption of 6-ACA on silica gel with various loading amounts was measured, and the spectra are illustrated in Fig. 3. At fairly large loading [Fig. 3(e), $\theta = 0.40$, where θ = surface coverage) the spectrum of the adsorbed sample is similar to that of neat 6-ACA in the solid state [Fig. 1(b)] i.e. both of the spectra exhibited $\nu_{as}CO_2{}^-$ at 1560 cm^{-1} and νNH_3^+ at 2700–2000 cm^{-1}. Drastic changes in the IR spectra were observed with a decrease in the amount of 6-ACA adsorbed (τ <0.003), where a new band appeared at 1655 cm^{-1} due to νC=O with a simultaneous decrease in the intensity of $\nu_{as}CO_2^-$ at 1560 cm^{-1}. Figure 3 also shows an increase in the intensity of νNH_2 in concomitant with the decrease in the intensity of νNH_3^+ on going to smaller τ values. Hence the adsorbed species is deduced to change successively from the species having CO_2^- and NH_3^+ groups as in the solid state to the neutral species having C=O, which corresponds to the carboxylic acid monomer, and NH_2 groups with a decrease in the loading amount as shown in Scheme 2. We have reported similar results that glycine is adsorbed on silica gel as species having C=O and NH_2

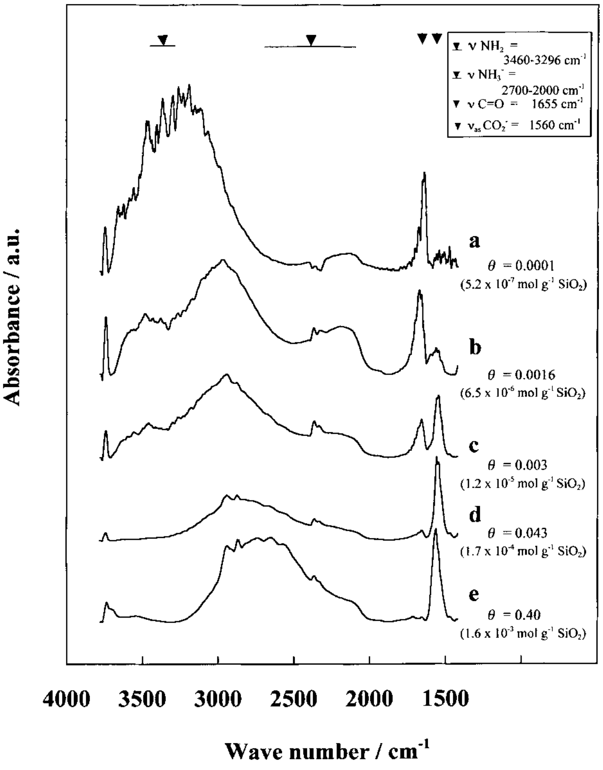
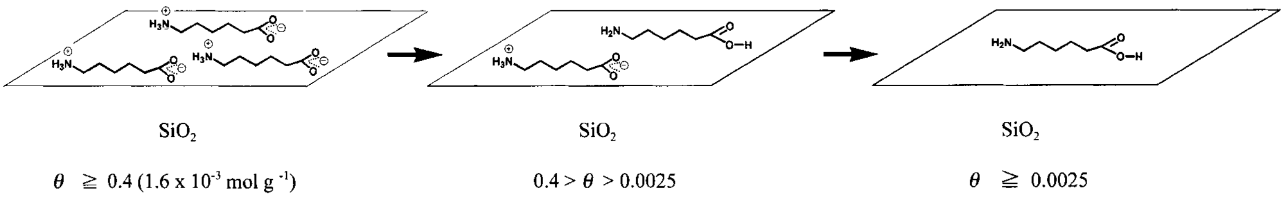


Figure 3. IR spectrum of 6-ACA on silica gel at various loadings. The adsorbed species changes successively from an amphoteric ion having CO_2^- and NH_3^+ groups to a neutral species having C=O and NH_2 with decrease in the loading amount



Scheme 2

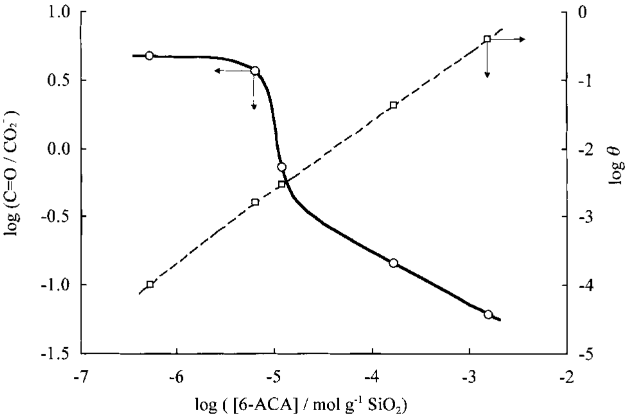


Figure 4. Molar ratio of carbonyl group to carboxylate anion ($C{=}O/CO_2^-$) in the adsorbed samples as a function of the loading amount of 6-ACA. The dashed line shows the surface coverage (θ) for each loading amount. 6-ACA is adsorbed as carboxylic acid at lower loadings and carboxylate anion at higher loadings

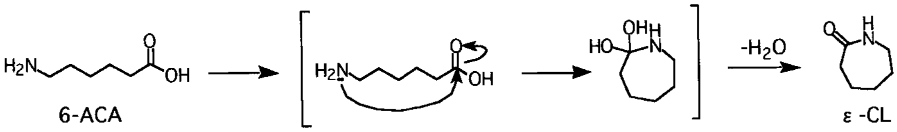
groups at an adequately low loading amount ($\tau = 0.0024$).[13]

Figure 4 shows the molar ratio of the carbonyl group to the carboxylate anion, $C{=}O/CO_2^-$, in the adsorbed samples determined by IR spectrometry as a function of the amount of 6-ACA loaded. At $\theta = 0.40$ the value of $C{=}O/CO_2^-$ was small (0.06), which indicates that almost of all of the carboxyl group exists as the carboxylate anion. The ratio increased moderately with decrease in τ and then increased drastically at $\theta = 0.0025$. These findings show that the dispersion of 6-ACA on the silica gel surface reduces the intermolecular interactions and concurrently changes the amphoteric ion to the corresponding neutral species.

It is assumed that the reactivity for the dehydration of the neutral species having C=O and NH_2 groups is high because revealing of the lone pair of electrons of the amino group causes easy attack on the neutral carbon center of the carboxyl group as shown in Scheme 3. In practice, both the yield and the selectivity for ε-CL increased with decrease in the loading amount of 6-ACA (Table 1, entries 1–3). On the other hand, fairly selective formation ε-CL proceeded even at $\theta = 0.095$ (Table 1, entry 2). The IR spectrum of this sample could be an intermediate of the two spectra (d) and (e) in Fig. 3, where 6-ACA exists mainly as an amphoteric ion having CO_2^- and NH_3^+. This adsorbed species cannot explain the fairly selective intramolecular dehydration. 6-ACA molecules at $\theta = 0.095$ are, nevertheless, assumed to be dispersed on the silica gel surface and reduced in the intermolecular interactions, presumably by the suppression of their translational movements. This would prevent the intermolecular reactions from yielding dimer or trimer. Accordingly, combined effects of dispersion and activation of 6-ACA by adsorption on the surface of silica gel would be significant for the selective formation of ε-CL with our method.

Water addition to adsorbed sample

To the adsorbed sample of 6-ACA ($\theta = 0.012$) was added 9.0 wt% of water and the mixture was subjected to the reaction. The product ε-CL was obtained in 68.3% yield with 92.3% selectivity as listed in Table 1 (entry 4). Consequently, this adsorption method is moderately insensitive to the addition of water. The effect of the addition of water to the adsorbed sample was monitored by IR spectrometry and the results are shown in Fig. 5. The absorption band at 1560 cm^{-1} due to $\nu_{as}CO_2^-$ remained in position with a decrease in intensity, but the band at 1655 cm^{-1} due to $\nu C{=}O$ shifted to near 1710 cm^{-1} with increase in intensity on addition of water [Fig. 5(a)–(c)]. The latter absorption suggests that the



Scheme 3

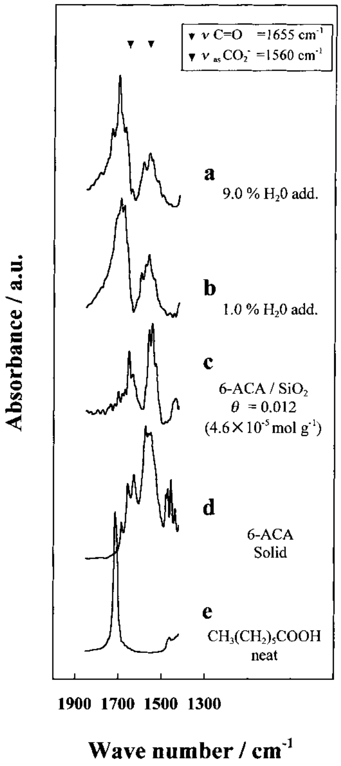


Figure 5. Change in IR spectrum of 6-ACA adsorbed on silica gel ($\theta = 0.012$) on addition of water. The amount of carboxylate anion decreased with addition of water

adsorbed species did not change to the dimer of carboxylic acid, because the characteristic band of νC=O of heptanoic acid [Fig. 5(e)] was exhibited at 1715 cm^{-1} and translational movement is required for formation of the dimer. Although the reason why the absorption of C=O shifted to higher wavenumber on addition of water is not clear at present, the species on the silica gel could readily be dehydrated to give ε-CL selectively. Suppression of the translational movements may promote the selective reaction.

CONCLUSION

When 6-ACA adsorbed on silica gel was treated in refluxing toluene, cyclodehydration proceeded to yield ε-CL selectively. IR measurement of the adsorbed 6-ACA on silica gel showed that adsorbed 6-ACA has COOH and NH_2 groups at the low surface coverage ($\theta < 0.043$), which would be active for selective dehydration with the aid of suppression of the intermolecular interactions. On the other hand, at relatively high surface coverage ($\theta = 0.10$) 6-ACA has $CO^{-}{}_2$ and NH_3^+ groups, which also gives a fairly selective reaction. In this case sufficient dispersion of 6-ACA on the silica gel would reduce the intermolecular reaction by repression of translational movement.

EXPERIMENTAL

General

Silica gel (Wako Chemicals; 200 mesh, for column chromatography) was dried at 110 °C overnight and stored in a desiccator. The specific surface area of 371 m^2 g^{-1} was determined by BET measurement. Authentic samples of 6-ACA and ε-CL were of guaranteed grade from Tokyo Chemical Industry. Sodium heptanoate was synthesized from heptanoic acid with 1.2 molar equivalent of metallic sodium, and hexylamine hydrochloride was synthesized from hexylamine with 1.5 molar equivalent of HCl. Both were recrystallized from water. Other materials were commercially available and used as received.

Quantitative analysis was performed with a Yanagimoto Model G2800F instrument equipped with Polyester FF column (1.5 m) for gas chromatography (GC) and with a Tokyo-Rikakiki EYELA PLC-10 system for high-performance liquid chromatography (HPLC) equipped with a TR-35-415F (ODS) column (30 cm) using water–methanol (2:8, w/w) plus 0.1 wt% of phosphoric acid as the eluent. β-Naphthol was used as an internal standard in all analyses.

Preparation of adsorbed sample and reaction procedure. Typically, the silica gel powder (10.0 g) was added to an aqueous solution (50 ml) of 6-ACA (60.3 mg, 4.6×10^{-4} mol), the mixture was allowed to stand for 8 h at room temperature with occasional shaking and the solvent was subsequently removed under reduced pressure. The adsorbed sample (10.0 g) described above was suspended in toluene (50 ml) and heated under reflux for 20 h using a Dean–Stark trap to collect the water formed. A reaction period of 20 h had been confirmed to be sufficient for completion of the reaction. After filtration of the solid it was thoroughly washed with distilled water (3 × 50 ml) and DMF (3 × 50 ml) successively. The combined washings and the filtrate were concentrated *in vacuo* and the product was analyzed by GC and/or HPLC. The yield of ε-CL was 89.6% with 10.2% of intact 6-ACA.

An adsorbed sample with 9.0 wt% of water added was prepared as follows: water (0.90 g) was introduced into a glass tube containing the adsorbed sample (10.0 g), then the tube was sealed and allowed to stand for 1 day at room temperature.

IR measurement. The IR absorption of 6-ACA adsorbed on silica gel was measured by Fourier transform IR spectrometry with a JASCO FT/IR-7000 infrared spectrometer equipped with DR-81 module for the diffuse reflection technique. The adsorbed sample was measured as a powder. Spectra were measured with 100 scans at 8 cm^{-1} resolution and obtained by ratioing the background spectra of adsorbent silica gel or water-added silica gel to those of adsorbed samples. The intensities of the IR absorption of νC=O and $\nu_{as}CO_2^-$ were converted into molarities by determining the relative ratio of absorption coefficients, $\varepsilon_{rel} = \varepsilon_{C=O}/\varepsilon_{CO^-2} = 0.89$.

Adsorption isotherm. To a 10 ml flask containing a solution of 6-ACA (1.31–105 mg, 0.999– 80.0 mmol l^{-1}) in methanol (10.0 ml) were added 100 mg of silica gel powder. The flask was tightly capped and immersed in an automatic shaker maintained at 25.0 ±0.2 °C. Adsorption equilibrium was attained after 8 h. The initial and final concentrations of 6-ACA in the solution were determined by HPLC.

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