Interaction of Ascorbic Acid with Silicic Acid

WEN-HUNG WU, TING-FONG CHIN, and JOHN L. LACH

Abstract □ Interaction of ascorbic acid with silicic acid in the solid state was studied using diffuse reflectance spectroscopic techniques. Surface degradation products from ascorbic acid breakdown were effectively observed using diffuse reflectance spectroscopy, whereas the corresponding transmittance spectral method did not give significant information concerning degradation products. Adsorption of ascorbic acid from methanol solution by silicic acid did not occur. However, after evaporation of the methanol, ascorbic acid did undergo strong interaction with silicic acid, probably through hydrogen bonding. Thermal degradation of ascorbic acid in the adsorbed state was found to be different from that in solution. In acid solution, furfural was a major degradation product; whereas in the adsorbed state, furfural could not be detected.

Keyphrases □ Ascorbic acid–silicic acid—solid-state interaction □ Silicic acid–adsorbed ascorbic acid—stability □ Thermal stability—ascorbic acid □ TLC—analysis □ Diffuse reflectance spectroscopy—analysis

Silicic acid, an almost completely inert adsorbent, has found considerable use as a support in chromatography and as a carrier material for some oil-soluble vitamins and other medicinal agents. The surface of silicic acid consists of a plane of exposed silicon atoms to which are attached covalent surface hydroxyl groups, or silanols, the only important adsorption sites. The adsorbed molecules interact with silanols by hydrogen bonding, in which the adsorbed molecule normally acts as an electron donor (1). Gueyne and Duffaut (2) reported complex formation between an alkaline silicate and organic acids, including ascorbic acid. Strohecker and Henning (3) stated that it is not suitable to employ silica gel plates for quantitative assay of ascorbic acid, since too much is lost on the silica gel. Since a loss of ascorbic acid has also been reported to occur when ascorbic acid is present in a vitamin preparation containing oil-soluble vitamins which have been adsorbed onto silicic acid, this study was undertaken to obtain information concerning the nature of this loss. This study also represents a continuing program in the investigation of drug–excipient interactions.

EXPERIMENTAL

Materials—Ascorbic acid (USP reference standard);[1] L-ascorbic acid, reagent grade, m.p. 190–193°;[2] silicic acid, average particle diameter, 3 μ;[3] dehydroascorbic acid;[4] levulinic acid;[5] furfural;[6] 2,6-dichlorophenolindophenol sodium;[7] and 2-diphenylacetyl-1,3-indandione-1-hydrazone, m.p. 241°,[8] were used.

Apparatus and Methods—All diffuse reflectance spectra (DRS) were taken according to the method of Lach and Bornstein (4) by using a spectrophotometer equipped with reflectance attachment.[9]

Determination of Ascorbic Acid—This was performed by the dye method described in USP XVII (5).

TLC for Identification of Degradation Products of Ascorbic Acid—Silica gel G plates (0.25 mm.) and a solvent system of chloroform–*n*-heptane (1:8) were used. Ten grams of darkened sample containing silicic acid, ascorbic acid, and its degradation products was continuously extracted in a continuous extraction apparatus with anhydrous ether for 24 hr. The ethereal extract was concentrated to 1 ml. and then reacted with 2-diphenylacetyl-1,3-indandione-1-hydrazone (DIH) in a mixture of methanol and chloroform using 1 drop hydrochloric acid as a catalyst. The solution was spotted on a plate together with chloroform solutions of a reaction product of furfural and DIH (F-DIH), levulinic acid and DIH (L-DIH), and DIH itself. After development, the plates were examined under UV light. Since DIH shows a bright-yellow fluorescence under UV light,

Table I—Thermal Degradation of Pure Ascorbic Acid at 100°

Time, hr.	Ascorbic Acid Found, mg.	% Degradation	Color Change
0	100	0	White
2	100	0	White
9	99.4	0.6	White
24	99.4	0.6	Slightly yellow
53.5	99.8	0.2	Yellow
140	99.5	0.5	Grey
192	99.4	0.6	Grey

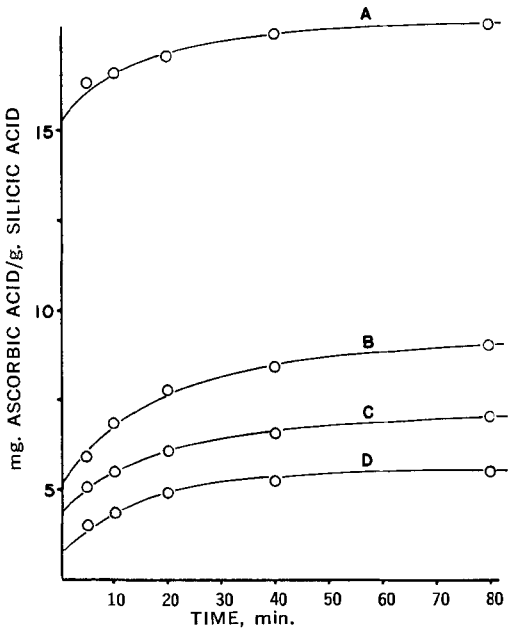


Figure 1—*Desorption and degradation of ascorbic acid (20 mg.) adsorbed on silicic acid (1 g.). Key: A, without heating; B, heated at 100° for 9.5 hr.; C, heated at 100° for 20.5 hr.; and D, heated at 100° for 40.0 hr.*

[1] U. S. Pharmacopeial Convention, Inc.
[2] Fisher Scientific Co.
[3] Mallinckrodt Chemical Works, St. Louis, Mo.
[4] Pierce Chemical Co., Rockford, Ill.
[5] Eastman Organic Chemicals, Rochester, N. Y.
[6] Fisher Scientific Co.
[7] K & K Laboratory, Inc.
[8] Aldrich Chemical Co., Milwaukee, Wis.

[9] Beckman model DB-G and Beckman reflectance attachment.

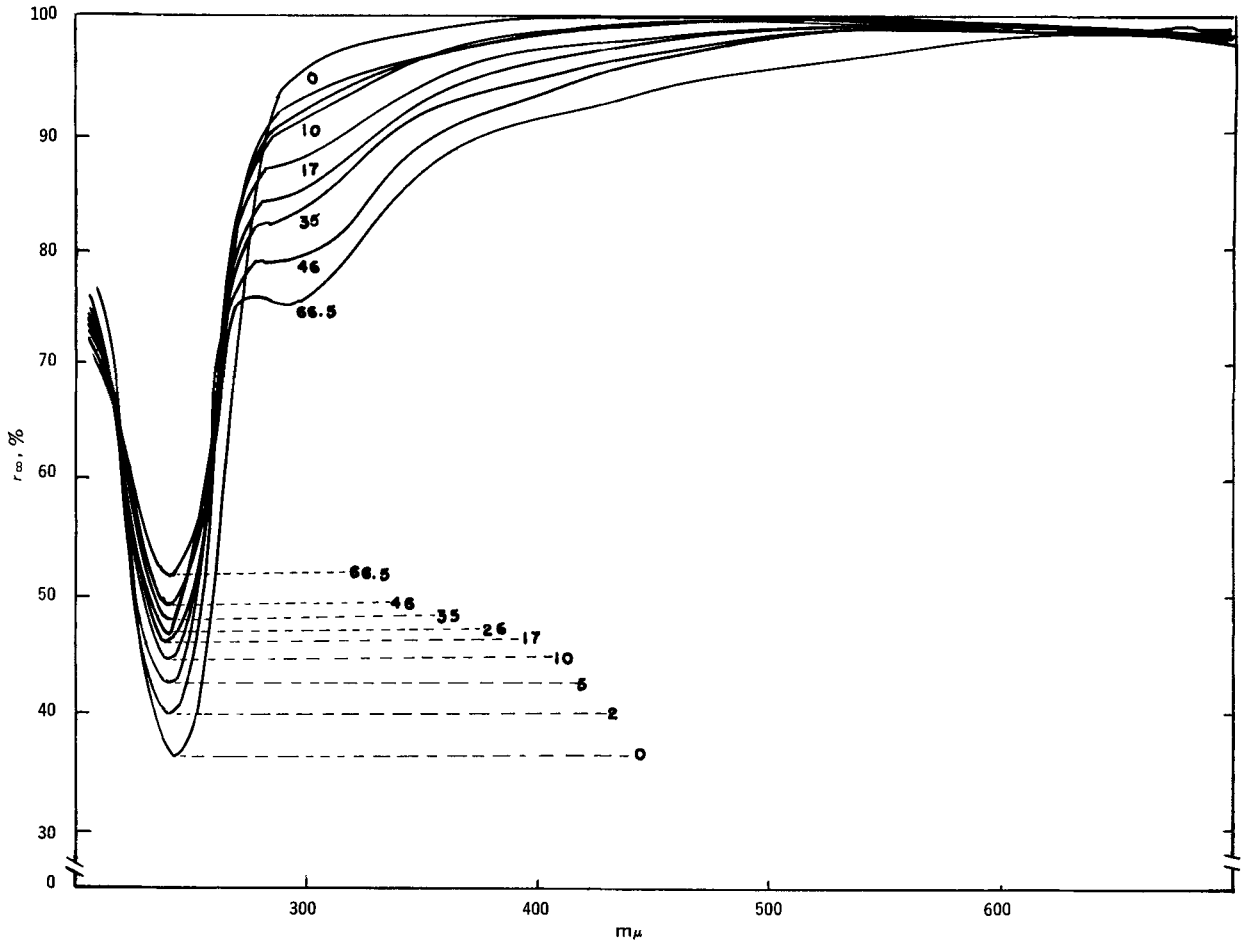


Figure 2—*Diffuse reflectance spectra showing the effects of heating ascorbic acid–silicic acid system at 100°. (The numbers shown are time in hours.)*

all spots containing the DIH moiety appeared as bright spots in the violet background.

RESULTS AND DISCUSSION

Stability of ascorbic acid in the solid state was first studied by heating 100 mg. each of finely powdered ascorbic acid in a number of 50-ml. beakers in a dry oven at 100 ± 0.5°. Quantitative determination of these solid samples was followed at varying time intervals, and the results are shown in Table I. The data in this table indicate that there is no apparent relationship between degradation of ascorbic acid and color change. It is probable that only the surface layer of each ascorbic acid particle was decomposed and that this degradation product(s) could act as a protecting film so that no further decomposition was observed within the time interval studied. Thermal stability of ascorbic acid has been previously studied by several workers (6–8), and their results indicated that pure ascorbic acid is thermally stable at elevated temperatures.

Since silicic acid is known to adsorb various compounds, adsorption of ascorbic acid by silicic acid in methanol solution was undertaken. Ten milligrams of ascorbic acid in 10 ml. methanol was equilibrated with varying quantities of silicic acid for 18 hr. under nitrogen; after centrifugation, the concentration of ascorbic acid in the clear supernatant liquid was determined, and the results are shown in Table II. Since the amount of ascorbic acid that remained in solution phase was approximately constant, it may be concluded that the adsorption of ascorbic acid by silicic acid from the methanol solution was negligible.

However, after complete evaporation of methanol in such equilibrated systems, ascorbic acid was strongly adsorbed to silicic acid since this acid was only very slowly removed from the adsorbent surface by metaphosphoric–acetic acids T.S. This is shown in Fig. 1, Curve A, in which 20 mg. of ascorbic acid/g. of silicic acid was equilibrated in methanol under nitrogen and the solvent evaporated at room temperature under vacuum. Accurately weighed portions of this dried sample were then titrated under nitrogen or after stirring at constant speed for a specified time. As is seen in Fig. 1, approximately 80 min. was required for desorption to occur. These results indicate that ascorbic acid is adsorbed to silicic acid on removal of the methanol and that this adsorption probably occurs through hydrogen bonding between the silanols on the silicic acid and the carbonyl oxygen of ascorbic acid. The lack of quantitative desorption of ascorbic acid as seen in Fig. 1, Curve A, may be attributed to its oxidation in the adsorbed state and will be discussed later.

Stability aspects of ascorbic acid adsorbed on silicic acid were also carried out. Portions of the methanol-equilibrated and vacuum-dried samples were heated at 100 ± 0.5° in a dry oven, and at various time intervals the intact ascorbic acid was determined. The results are shown in Fig. 1, Curves B–D. From this figure and Table

Table II—Adsorption of Ascorbic Acid from Methanol Solution by Silicic Acid

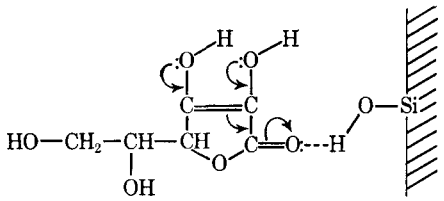
Ascorbic Acid Added, mg.	Silicic Acid Added, g.	Ascorbic Acid Found, mg.[a]
10	0	9.69
10	0.020	9.65
10	0.050	9.65
10	0.100	9.72
10	0.200	9.79
10	0.300	9.79

[a] When 10 mg. of ascorbic acid in 10 ml. methanol was allowed to stand in the dark without tumbling, 9.96 mg. was found after 18 hr.

Table III—Correlation of Reflectance and Degradation of Ascorbic Acid in Adsorbed State

Time for Heating at 100°, hr.	Data from DRS: r_∞ λ245 mμ, %	Data from DRS: $f(r_\infty)$	Ascorbic Acid Found, mg.
0	36.5	0.5524	60
2	40.0	0.4500	56.2
5	42.8	0.3822	—
10	44.9	0.3381	51.9
17	46.2	0.3133	47.8
26	47.0	0.2988	45.0
35	48.1	0.2800	44.1
46	49.2	0.2632	43.9
66.5	51.8	0.2243	42.0

I, it is evident that degradation of ascorbic acid is significantly greater in the adsorbed state than in pure powder form. This accelerated degradation rate may be due simply to a difference in the total surface area, since in this adsorbed state a larger number of ascorbic acid molecules are available for degradation than in the surface of the pure powder. Or it may be due to the fact that in this adsorbed state, as shown in Scheme I, hydrogen bond formation between the carbonyl oxygen of ascorbic acid and the silanol



Scheme I

hydrogen requires a strong bonding of the lone pair electrons on the carbonyl oxygen to the silanol hydrogen. This can induce a general electron shift through the α,β-enone π-orbitals toward this new bond, so that the dissociation of the two hydroxy hydrogens on the

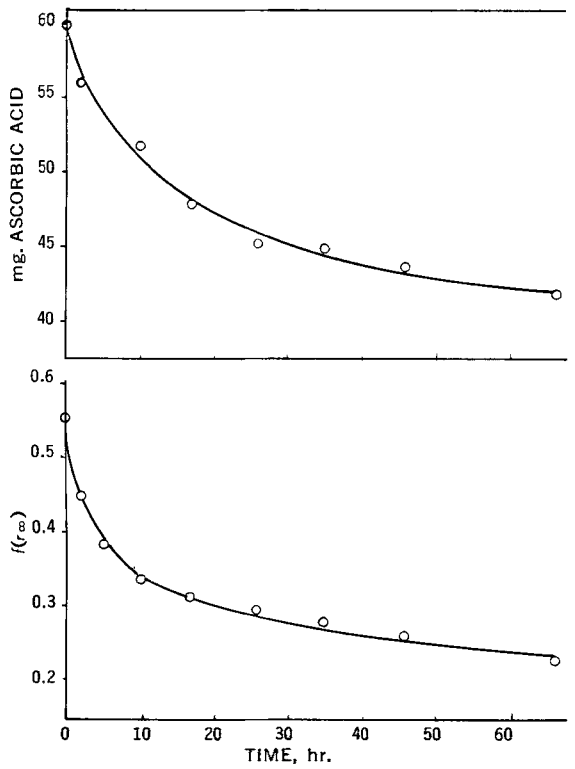


Figure 3—*Correlation of reflectance and degradation of ascorbic acid in adsorbed state.*

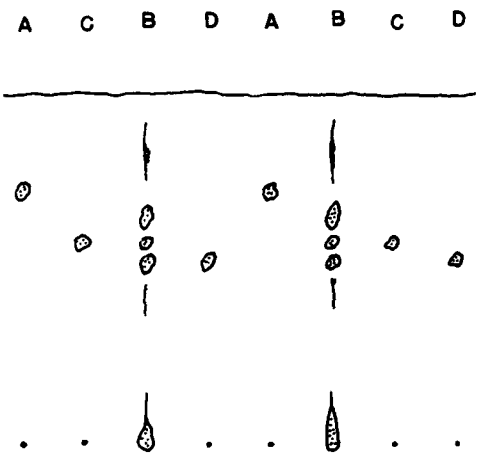


Figure 4—*TLC showing thermal degradation products of ascorbic acid–silicic acid system. Key: A, F-DIH, R_f = 0.71; B, ethereal extract reacted with DIH; C, L-DIH, R_f = 0.58; and D, DIH, R_f = 0.53.*

2- and 3-positions in ascorbic acid is enhanced. This increased dissociation may facilitate the oxidation of ascorbic acid to various carbonyl compounds, presumably through dehydroascorbic acid.

The degradation of pure ascorbic acid in the solid state was also studied using DRS. When a portion of the faintly yellow sample shown in Table I was appropriately diluted with acidified water and the transmittance spectrum taken, the solution showed an absorption maximum at 245 mμ. However, when another portion of the same sample was mixed with silicic acid and the reflectance spectrum taken, two absorption maxima appeared. The one at 245 mμ corresponded to the transmittance spectrum of the acidified ascorbic acid solution. The other, which appeared at 275 mμ, might be a composite maximum due to the various carbonyl compounds produced from the surface degradation of ascorbic acid. Although the quantity of degradation products formed from pure ascorbic acid was small, as shown in Table I, they are mainly concentrated on the surface and are effectively shown in the reflectance spectrum. However, in solution state, they are homogeneously mixed with the intact ascorbic acid molecules, so that the overwhelming amount of ascorbic acid present can sufficiently mask any spectral effects of this small quantity of degradation products. This clearly illustrates the advantage of the DRS method in studying degradation occurring at the surfaces.

When 60 mg. of ascorbic acid was equilibrated with 1 g. of silicic acid in methylene chloride and the dried sample was heated at 100 ± 0.5°, the reflectance spectra taken at varying time intervals showed different intensities; these are given in Fig. 2. As is illustrated in this figure, the intensity of the maximum at 245 mμ gradually decreased with time, whereas a new maximum at about 300 mμ appeared with increasing intensity. This second maximum at 300 mμ is different from that observed in the degradation of pure ascorbic acid, in which case the second maximum appeared at 275 mμ. This suggests that the degradative mechanisms might be different. Along with the spectra, quantitative determinations of ascorbic acid in these equilibrated and heated samples were carried out, and the results are shown in Table III and Fig. 3. For purposes of comparison, reflectance readings, r_∞, at 245 mμ were converted to remission functions, $f(r_\infty)$ since the remission function is directly related to concentration (9). Examination of Fig. 3 does show this remission function concentration dependency which is maintained in the degradated sample, suggesting that quantitized degradation in the solid state can be studied by this technique.

With respect to ascorbic acid it is interesting to note that its degradation products from aqueous solution have been determined by Otani (10) using TLC, and reported to be dehydroascorbic acid, 2,3-diketo-1-gulonic acid, 2-keto-1-gulonic acid, and furfural. Formation of furfural from aqueous solution of ascorbic acid was also discussed by various workers (11–13), the rate of furfural formation being studied in detail by Finholt *et al.* (14).

However, in the present study furfural was not found as part of the degradation products resulting from the breakdown of ascorbic acid in the adsorbed state. Instead, levulinic acid was detected

on thin-layer plates as described in the *Experimental* section. The DIH reagent was used because of its high reactivity toward carbonyl compounds (15, 16). Thermal degradation products of this ascorbic acid–silicic acid system are shown in Fig. 4. Examination of the chromatogram does indicate the absence of furfural, the possible presence of levulinic acid, and, in addition, other unidentified degradation products, and strongly suggests that ascorbic acid in this adsorbed state undergoes a different type of degradation from that in aqueous solution. Although furfural was not detected in this system, it is still possible that any furfural formed could have volatilized from the solid surface or undergone polymerization. It is highly unlikely, however, that levulinic acid results from furfural degradation, since Lamden and Harris (11) pointed out that the formation of furfural in solution degradation does not result from dehydroascorbic acid which, as mentioned before, is probably the first step in the oxidation of ascorbic acid in the adsorbed state. It is, therefore, highly likely that the degradation pathway in the adsorbed state may be quite different from that in solution.

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Electrostatic Interaction of Oil Droplets with Adsorbed Surface-Active Ions in Dilute Electrolyte Solutions

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Abstract □ Using the Haydon-Taylor model in which the surfactant head groups are situated at some distance from the oil surface, the interaction energy of electrostatic repulsion (V_R) between oil droplets in dilute electrolyte solutions is derived for the two cases: constant-surface potential and constant-surface charge. For comparison, the repulsive energy is also derived for the constant-surface charge case without the effect of this adsorbed layer model. The Haydon-Taylor model accounts for the penetrability of the electrolyte and dielectric constant in the adsorbed surfactant layer of varying thickness, the degree of surface coverage, particle-size effect, ionic strength, and the dielectric constant in the bulk solution. In the constant-potential case, the resulting V_R equation is identical to the classical Derjaguin, Landau, Verwey, and Overbeek (DLVO) one. Computations show that as flat plates and spheres approach each other, V_R (constant-surface charge with impenetrable adsorbed layer) > V_R (constant-surface charge with penetrable adsorbed layer) > V_R (constant-surface potential). Because of the possible 50- to 100-fold difference in magnitude between them, proper choice of the model is important when considering application of the theory to the rigorous kinetic treatment of the coalescence of o/w emulsions and flocculation of suspensions.

Keyphrases □ Oil droplets, electrostatic interaction—adsorbed surface-active ions □ Electrolyte solutions—oil droplets, adsorbed surface-active ion interaction □ Repulsive interaction—flat plates, spheres □ Emulsions—particle collision probability

In those dispersed systems in which the primary barrier to flocculation (or coalescence) is electrical, the classical theory of the repulsive interaction of overlapping electrical double layers between two particles combined with the attractive interaction due to dispersion forces is used. Moreover, the usual model employed for the repulsive energy requires that the surface potential remains constant during the collision of particles, although the model on constant-surface charge, in which case the surface potential increases during the encounter, is applicable in most dispersed systems (1).

Frens *et al.* (2, 3) showed that the collision of silver iodide colloidal particles in aqueous electrolyte solutions was more appropriately explained by the constant-surface charge condition. They employed the exact solution of the Poisson-Boltzmann equation in the form of elliptical integrals. Recently, while examining the question of the surface potential or charge remaining constant during the mutual approach of particles, Jones and Levine (4) derived approximate expressions in series form, and Muller (5) derived exact equations expressed as elliptical integrals.

Haydon and Taylor (6–8) proposed a model for the adsorption of ionic surface-active agents at the oil/water interface, allowing for the penetration of mobile ions into the adsorbed layer of surfactant molecules situated at some equilibrium distance from the interface. They calculated the potential in the aqueous surface phase and related it to surface-pressure area measurements. The Poisson-Boltzmann equation was