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Effect of Temperature on Solubilization of Aromatic Compounds by Didodecyldimethylammonium Bromide Vesicles

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Abstract : The solubilization of aromatic compounds (phenol, benzoic acid, benzene, ethylbenzene) in the aqueous solutions of didodecyldimethylammonium bromide (DDAB) vesicles was investigated as a function of temperature by measuring the solubilization equilibrium constants (K_{vesicle}), the microviscosity of the vesicle bilayer membrane, and the degree of the dissociation (α) of the counter-ion from the vesicle. Benzene and ethylbenzene are only slightly solubilized below the temperature of 8°C, and K_{vesicle} between the DDAB vesicle and the bulk aqueous phase shows an abrupt increase at the temperature range 8~10°C. The fluorescence measurement indicates that the phase transition temperature (T_c) of the DDAB vesicle is about 9.5°C. The solubilization of benzene and ethylbenzene will depend on the microviscosity of the vesicle bilayer membrane. The comparison of K_{vesicle} with the partition coefficient (K_{dodecane}) of the aromatic solute between the *n*-dodecane phase and the water phase suggests that the benzene molecule is solubilized at the vesicle surface where the π electron cloud of the benzene interacts with the changed surfactant head groups, and that the ethylbenzene molecule is located inside the bilayer membrane. On the other hand, K_{vesicle} values of phenol and benzoic acid exhibit a maxima at *ca.* T_c of DDAB, and the α value of the vesicle also has a maximum around T_c . It is thought that the solubilization of phenol and benzoic acid depends on the degree of the DDAB vesicle charge, and these polar solutes are located at the vesicle surface because the polar groups are attracted electrostatically to the charged head groups of DDAB.

Key words : solubilization equilibrium constant, vesicle, aromatic compound, microviscosity, degree of dissociation

1 Introduction

Solubilization techniques have been utilized in many fields such as washing processes, surfactant-based wastewater treatments, reconstitution of protein, paints, cosmetics, *etc.* However, in many applications and basic research on solubilization, it is surfactant micelles that have been very often employed as solubilizers; few studies have been made on the solubilization of organic solutes in liposomes and/or surfactant vesicles.

On the other hand, recently vesicles have attracted attention as biomimetic membranes,

drug carriers^{1)~4)}, and new organic synthesis sites⁵⁾. Furthermore, we have expected vesicles to be solubilizers in a colloid enhanced ultrafiltration (CEUF) process^{6),7)}, that can remove organic solutes from the waste water stream⁸⁾. Solubilization in vesicle aqueous solutions will be a subject of important fundamental research due to the potential applications.

In only a few physicochemical studies on vesicle solubilization, the investigation of Dill *et al.* on a phospholipid vesicle-hexane system⁹⁾, and that of Omann *et al.* on a dioctadecyldimethylammonium chloride vesicle-ethylene derivative system¹⁰⁾, have indicated that the solubilization of organic solutes into vesicles depends on the microviscosity of the vesicle bilayer membranes. On the other hand, there have been surprisingly few studies on the solubilization of polar organic solutes by vesicles and on the solubilization sites in vesicle bilayer membranes.

In this work, the effect of temperature on the solubilization in the aqueous solutions of didodecyldimethylammonium bromide (DDAB) vesicles was investigated using four solubilizes with different polarities, which are phenol and benzoic acid as polar compounds, and benzene and ethylbenzene as non-polar solutes. The solubilization results are given in terms of the infinite-dilution values of solubilization equilibrium constants of these aromatic solutes between vesicle and bulk-aqueous phases. The infinite values are expected to directly reflect the solute-vesicle interactions. The interaction between the vesicle bilayer membrane and the aromatic solutes, and the solubilization sites of the solutes will be discussed, as the solubilization equilibrium constants are correlated to the vesicular microviscosity and the degree of dissociation of the counter-ion from the vesicle.

2 Experimental Section

2.1 Materials

Didodecyldimethylammonium bromide (DDAB) was purchased from Eastman Kodak Co., and was used after recrystallized several times with acetone. Phenol, benzoic acid and ethylbenzene were obtained from Tokyo Kasei Kyogyo Co., and benzene was from Dojin Chemical Co. These compounds were of special grade and employed without further purification. 8-anilinonaphtalene-1-sulfonate ammonium salt (ANS) (the highest grade) from Wako Pure Chemical Co. and *n*-dodecane (special grade) from Tokyo Kasei Kogyo Co. were used as received. Water was distilled water for injection JP (Japanese Pharmacopoeia), obtained from Ohtsuka Pharmacy Co.

2.2 Preparation of DDAB Vesicle and the Solutions Solubilizing Aromatic Solutes.

The preparation of 10 mM DDAB vesicle aqueous solution was performed by ultrasonication of surfactants in water for 120 min with a Bransonic cleaner (power 125 W; Branson Cleaning Equipment Co., model B-220). The solution temperature under sonication was $30 \pm 5^\circ\text{C}$. The mean diameter of DDAB vesicles, determined by the dynamic light-scattering method, was 17.5 nm, as reported previously^{8),11)}.

Vesicle aqueous solutions solubilizing aromatic solute were prepared by adding different amounts of the solute to 10 mM DDAB vesicle solution, thermostated in advance at a temperature of the solubilization experiments for 12 h. The vesicle solutions were permitted to equilibrate for 36 h at the experimental temperature.

2.3 Measurements of Solubilization Equilibrium Constants of Aromatic Solutes between Vesicle Phase and Bulk Water Phase.

Solubilization equilibrium constants (*K*) of aromatic solutes between the vesicle and bulk aqueous phases were measured by the equilibrium dialysis (ED) method. Commercial equilibrium dialysis cells (Sanplatec Co.) with cellulose acetate membranes were utilized. The membrane have a 6000-Da molecular weight cutoff, and they were washed thoroughly in water for 12 h before use. The solute solubilized solution was placed on one side of the membrane (retentate), and the other side (permeate) contained water. The ED cells were ther-

mostated at a fixed temperature for 36 h, even though all solutions were equilibrated within 26 h, and then the concentrations of aromatic solute and surfactant in the retentate and permeate solutions were determined by UV spectroscopy (Shimadzu Co., model MPS-2000) and Orange II method^{13),14)} respectively, as reported previously⁸⁾. Finally, K values were calculated using the estimated DDAB and aromatic solute concentrations.

2·4 Measurements of the Polarization Degree of ANS Fluorescence.

Ethanol solution of ANS was evaporated *in vacuo* at *ca.* 40°C. The resultant ANS film was dissolved in 10 mM DDAB vesicle solutions, to give the ANS concentration of 0.5×10^{-3} mM. The ANS-containing vesicle solutions were allowed to stand for 24 h at a fixed temperature.

Fluorescence of ANS was detected using Spectrofluorescencemeter RF-3000 (Shimadzu Co.) with polarizer at different temperature. Measurements were performed at an excitation wavelength of 380 nm and emission wavelength of 465 nm. The degree of fluorescence polarization was estimated on the basis of the equation¹⁴⁾.

$$P = \frac{I_{//} - I_{\perp}}{I_{//} + I_{\perp}} \quad (1)$$

where $I_{//}$ and $I_{\perp}$ are the emission intensity detected through polarizer oriented parallel and perpendicular to the polarization direction of excitation light.

2·5 Measurements of the Ionization Degree of DDAB Vesicles.

The degree of the dissociation (α) of the counter-ion Br^- from DDAB vesicles was estimated by measuring the free bromide-ion concentration in the vesicle solution. The electrical potential of the electrode (Orion Research Inc., model 9435BN) responding selectively to the bromide ion in DDAB solutions was measured by a potentiometer (Orion Research, model 920A) with a saturated calomel electrode (Iwaki glass Co., Tokyo, model C002) as the reference electrode. The potential values were converted to the concentration of bromide ion using the Nernst equation^{15),16)} and then the Br^- concentration was divided by the surfactant concentration to give the dissociation degree α .

2·6 Measurements of the Partition Coefficient of Aromatic Solute between *n*-Dodecane Phase and Water Phase.

Water, *n*-dodecane and a small amount of aromatic solute were added to the sample tube; subsequently the tube was thermostated for 36 h at a fixed temperature, and then the concentration of the solute in both phases was determined spectrophotometrically. The partition coefficients $X_{\text{dodecane}}/X_{\text{water}}$, in which X_{dodecane} and X_{water} indicate mole fractions of the solutes in *n*-dodecane and water phases respectively, were measured for several different concentrations of solute, and the infinite-dilution values (K_{dodecane}) were estimated by extrapolating $X_{\text{dodecane}}/X_{\text{water}}$ to the solute concentration of 0.

3 Results and Discussion

3·1 Concentration Dependence of Solubilization Equilibrium Constants of DDAB Vesicle-Aromatic Solute Systems

To estimate the infinite-dilution of solubilization equilibrium constants (K_{vesicle}), it is necessary to determine the dependence of the solubilization on the solute concentration. The solubilization equilibrium constant (K) of an aromatic solute in an aqueous vesicular solution is defined as

$$X = \frac{X_{\text{vesicle}}}{K_{\text{bulk}}} \quad (2)$$

where X_{vesicle} is the mole fraction of the aromatic solute in the vesicular phase, which is the ratio of the molar concentration of the solubilized solute to the total molar concentration of surfactant and aromatic solute in the vesicular phase, and X_{bulk} is the mole fraction of the monomeric aromatic solute in the bulk aqueous phase.

In this study, the DDAB concentration in the permeate solution after the dialysis experi-

ment was always lower than 7×10^{-2} mM. Considering that the micellar-forming concentration (cmc) of DDAB is 8×10^{-2} mM at 30°C , decided by the solution conductivity measurement, there will exist few or no DDAB micelles in the permeate solution of the ED cell. Therefore, the K values can be calculated from the equation

$$K = \frac{\frac{[O]_{\text{ret}} - [O]_{\text{per}}}{[O]_{\text{per}} + C_w + [S]_{\text{per}}}}{\frac{[O]_{\text{ret}} - [O]_{\text{per}} + [S]_{\text{ret}}^{\text{ves}}}{[O]_{\text{per}}}} \quad (3)$$

where $[O]$ and $[S]$ indicate the concentrations of aromatic solute and DDAB, respectively, C_w is the molarity of water, the subscripts ret, per, and ves represent the retentate side, permeate side, and the surfactant in vesicle form, respectively. In the case of $[O]_{\text{per}} \ll C_w$ and $[S]_{\text{per}} \ll C_w$, eq (3) can be expressed by

$$K = \frac{\frac{[O]_{\text{ret}} - [O]_{\text{per}}}{C_w}}{\frac{[O]_{\text{ret}} - [O]_{\text{per}} + [S]_{\text{ret}}^{\text{ves}}}{C_w}} \quad (4)$$

where $[S]_{\text{ret}}^{\text{ves}}$ is 10 mM because the DDAB concentration in monomeric form is much lower than that in vesicle form.

Figure 1 shows the change in K against X_{vesicle} for various aromatic solutes at the temperature of 30°C . As can be seen in this figure, the solubilization equilibrium constants for phenol and benzoic acid decrease almost linearly with increasing X_{vesicle} , while those for benzene and ethylbenzene show little solute concentration dependence. This tendency is also observed at other temperatures. It is thought that phenol and benzoic acid are solubilized more strongly by DDAB vesicles in the less solute-concentrated solution than in the more concentrated one. The infinite dilution of solubilization equilibrium constants (K_{vesicle}) can be estimated by extrapolating K (X_{vesicle}) to $X_{\text{vesicle}} = 0$. As can be seen from the intercept values of K - X_{vesicle} curves in the figure, K_{vesicle} decreases in order of benzoic acid > ethylbenzene > phenol > benzene. In contrast, the infinite-dilution of partition coefficients (K_{dodecane}) of the so-

Fig. 1 Dependence of Solubilization Equilibrium Constants (K) for Aromatic Compounds in DDAB Vesicles on Intravesicular Mole Fraction (X_{vesicle}) of solute 30°C .

$\circ$ benzoic acid, $\diamond$ ethylbenzene, $\blacksquare$ phenol, and $\triangle$ benzene.

lutes between *n*-dodecane and water phases were 1.8 for benzoic acid, 18000 for ethylbenzene, 1340 for benzene and 0.9 for phenol. The order of infinite-dilution values of solubilization equilibrium constants is in disagreement with that of K_{dodecane} of the aromatic solutes, and therefore will be independent of the solute hydrophobicity.

3.2 Temperature Dependence of Infinite-Dilution of Solubilization Equilibrium Constants.

Figure 2 shows the infinite-dilution of solubilization equilibrium constants (K_{vesicle}) at various temperatures. In benzene and ethylbenzene, an abrupt change in K_{vesicle} is observed in the temperature range of 8~10°C. Further, the K_{vesicle} below 8°C is much lower than that above 10°C.

On the other hand, for phenol and benzoic acid, the K_{vesicle} is found to exhibit maximum values at approximately 10°C. It should be noted that, even at low temperatures, these solutes are solubilized in DDAB vesicles, and that K_{vesicle} values below 8°C are rather larger than those at the temperature range 25~30°C. The K_{vesicle} value for benzoic acid decreases by as much as a factor of about 1/3 with an increase in temperature from 10°C to 30°C, while for phenol, it decreases *ca.* 50% in the same range of temperatures.

Undoubtedly, the solubilization equilibrium is affected more or less by the hydrophobicity of solubilizates. We therefore employed the partition coefficient (K_{dodecane}) of the aromatic solute between the *n*-dodecane phase and the water phase, to normalize the K_{vesicle} for the temperature dependence of the solute hydrophobicity.

The K_{vesicle} of the solutes were divided by their K_{dodecane} at the equivalent temperatures. The relationship between the normalized solubilization equilibrium constants ($K_{\text{vesicle}}/K_{\text{dodecane}}$) of solutes and temperature is shown in Fig. 3. As can be seen in the figure, $K_{\text{vesicle}}/K_{\text{dodecane}}$ -temperature curves are nearly similar in type to their own K_{vesicle} curves shown in Fig. 2. In other words, $K_{\text{vesicle}}/K_{\text{dodecane}}$ values for benzene and ethylbenzene show a sudden change, and phenol and benzoic acid have a maxima in the vicinity of 10°C.

Fig. 2 Relationship between the Infinite-dilution of Solubilization Equilibrium Constants (K_{vesicle}) and Temperature.

Fig. 3 Dependence of Normalized Solubilization Equilibrium Constants ($K_{\text{vesicle}}/K_{\text{dodecane}}$) on Temperature. K_{dodecane} is the infinite-dilution of partition coefficient of solute between *n*-dodecane phase and water phase.

3.3 Solubilization of Benzene and Ethylbenzene

The microviscosity of the DDAB vesicle bilayer was revealed by the fluorescence polarization (*P*) of ANS, which binds to the vesicle surface¹⁴⁾, as a function of temperature in Fig. 4. As can be seen in the figure, the rapid change of *P* value with an increase of temperature was observed in the range of 8~11°C, indicating that the microviscosity of the DDAB vesicle bilayer decreases abruptly. It has been reported that DDAB vesicles prepared by an ultra-

Fig. 4 Change in the Degree of Fluorescence Polarization (*P*) of ANS in DDAB Vesicles against Temperature.

sonication method display a phase transition from the gel state to the liquid crystal state around 8°C¹⁴). This temperature is in fair agreement with the rapid change of P observed in Fig. 4. In DDAB vesicle used in this work, the gel-liquid crystal phase transition clearly occurs between 8 and 11°C. The phase transition temperature (T_c), determined from the mid-point of the phase transition, is about 9.5°C.

From Fig. 3, it is found that T_c of the DDAB bilayer membrane agrees well with the temperature at which $K_{\text{vesicle}}/K_{\text{dodecane}}$ values of benzene and ethylbenzene show a strong change, and these solutes are solubilized in the *fluid state* of the vesicle bilayer membrane above T_c . The solubilization of non-polar solutes, ethylbenzene and benzene, clearly depends on the microviscosity of the vesicle bilayer membrane.

It should be noted that the $K_{\text{vesicle}}/K_{\text{dodecane}}$ values of benzene above T_c are about 5.5. Assuming that the vesicle bilayer membrane interior is hydrocarbon-like, and the solute is located inside the membrane, the $K_{\text{vesicle}}/K_{\text{dodecane}}$ value must be approximately 1. On the other hand, previous studies^{17),18)} have reported that the π electron cloud of the benzene ring interacts with the electric field induced by the cationic charge of surfactant head groups. This interaction should enhance the partition of the solute into the DDAB bilayer membrane. $K_{\text{vesicle}}/K_{\text{dodecane}}$ of benzene larger than unity will suggest that benzene molecules are located at the vesicular surface with interaction to the DDAB head groups.

In contrast, the ethylbenzene molecule is thought to be solubilized inside the DDAB membrane without its own benzene ring attracted to the DDAB head groups, because the $K_{\text{vesicle}}/K_{\text{dodecane}}$ value is approximately 1. The transfer of alkane from water to the hydrocarbon medium is stabilized by the dehydration¹⁸⁾. The deeper solubilization site of ethylbenzene from the vesicular surface than benzene seems to result from the hydrophobic property of the ethyl group.

3.4 Solubilization of Phenol and Benzoic Acid vs. DDAB Vesicle Charge

From Fig. 3, one should note that K_{vesicle} values of phenol and benzoic acid are about three and four orders of magnitude larger than their K_{dodecane} values, respectively. It seems that phenol and benzoic acid interact strongly with the particular region, present in DDAB vesicles but not in *n*-dodecane, in other words, the hydrophilic region of the vesicles.

Figure 5 shows the relationship between the degree of the dissociation (α) of the counter-ion Br^- from DDAB vesicles and temperature. It is found that the counter-ion dissociation

Fig. 5 Relationship between the Degree of Dissociation (α) of Br^- from DDAB Vesicles and Temperature.

degree exhibits a maximum value at 10°C. The polar groups such as phenolic hydroxyl and/or carboxyl groups seem to favor electrostatically the positive charge of DDAB, because these groups dissociate, and are negatively charged in aqueous solutions.

Figure 6 shows the α dependence of the normalized solubilization equilibrium constants ($K_{\text{vesicle}}/K_{\text{dodecane}}$) of phenol and benzoic acid. As can be seen in the figure, for both solutes, $K_{\text{vesicle}}/K_{\text{dodecane}}$ values increase with an increase in the dissociation degree, except the data for 30°C. It is clear that the solubilization of these polar solutes depends principally on the charged degree of DDAB vesicles. These solutes will be located at the DDAB vesicular surface with the polar groups of solutes attracted to the charged head groups.

In addition, the $K_{\text{vesicle}}/K_{\text{dodecane}}$ of phenol was divided by that of benzoic acid at each temperature. Figure 7 indicates that the relationship between the ratio of $K_{\text{vesicle}}/K_{\text{dodecane}}$

Fig. 6 Normalized Solubilization Constants ($K_{\text{vesicle}}/K_{\text{dodecane}}$) for Benzoic Acid and Phenol as a Function of Temperature.

Fig. 7 Dependence of $K_{\text{phenol}}/K_{\text{benzoic acid}}$ Values on the Degree of Dissociation (α) of Br^- from DDAB Vesicles.

K_{phenol} and $K_{\text{benzoic acid}}$ are the normalized solubilization equilibrium constants ($K_{\text{vesicle}}/K_{\text{dodecane}}$) of phenol and benzoic acid, respectively.

of phenol to that benzoic acid and α . The ratio changes only slightly with the dissociation degree, compared to the α dependence of $K_{\text{vesicle}}/K_{\text{dodecane}}$ of phenol and benzoic acid shown in Fig. 6. This would indicate that the effect of the vesicle charge is affecting the solubilization of these two solutes in a similar manner at the fixed temperature, namely at each α value of DDAB vesicle. Furthermore, it is found that $K_{\text{vesicle}}/K_{\text{dodecane}}$ of benzoic acid is larger than $K_{\text{vesicle}}/K_{\text{dodecane}}$ of phenol by a factor of *ca.* 5. The polarity of benzoic acid is higher than that of phenol, as can be seen by the $\text{p}K_{\text{a}}$ values of these solutes; the $\text{p}K_{\text{a}}$ for phenol is 9.82 at 25°C and for benzoic acid it is 4.18 at 25°C¹⁹⁾. The larger $K_{\text{vesicle}}/K_{\text{dodecane}}$ of benzoic acid would result from the relatively strong electrostatic attraction force between the DDAB head group and the solute polar group, compared to phenol.

$K_{\text{vesicle}}/K_{\text{dodecane}}$ values of phenol and benzoic acid at 30°C were larger than predicted by the dependence of $K_{\text{vesicle}}/K_{\text{dodecane}}$ of the solutes at temperatures under 30°C. On argument supporting this result is that the microviscosity of the DDAB vesicle bilayer membrane at 30°C affects the solubilization of the aromatic solute. As can be seen in Fig. 6, $K_{\text{vesicle}}/K_{\text{dodecane}}$ values at 30°C are larger than at 5°C, although there is little difference in α values between 5°C and 30°C. It seems that the solute can take the relatively favorable configuration to interact with the surfactant molecule in the *fluid* state membrane compared to the *gel* state membrane.

Finally, the following effects are thought to roughly explain the temperature dependence of the dissociation degree of DDAB vesicles. It is known that the area of surfactant head groups in vesicles increases during the phase transition from a gel state to the liquid crystal state^{20),21)}. This enlargement of the head group area may be expected to be supported by the increase in the electrostatic repulsive forces between head groups, *i.e.*, head group ionization. In contrast, the rise of temperature generally tends to cause decreased hydration of the surfactant head group, as pointed out for ionic micelle systems²²⁾, which will lead to the depression of the ionization of head groups in vesicles. The relative magnitude of these two opposing effects on head group ionization seems to determine α values of DDAB vesicles shown in Fig. 5. Thus, it appears that the increase in α with temperature from 8°C, at which the phase transition begins, to 10°C reflects the enlargement of the area of DDAB head groups by the phase transition, and the decrease in α beyond 10°C is due to dehydration of DDAB head groups in vesicles.

However, these effects are not sufficient to solve the abrupt increase of α values below 8°C. According to the ANS fluorescence polarization measurement (Fig. 4), below the temperature of 8°C, the DDAB vesicle is not in phase transition. Therefore, the increase of α will result from factors other than the enlargement of the DDAB head group area. Further studies on the temperature dependence of DDAB vesicle ionization are in progress.

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ミノ-16-メチルオクタデカン-1,3,4-トリオールであり、セラミド-IIでは*N*-2-ヒドロキシヘキサデカノイル-2-アミノ-16-メチルオクタデカン-1,3,4-トリオールであった。

セトウチマイマイ内臓部のセラミドの長鎖塩基で最も注目すべき特徴は分枝長鎖塩基が多量に存在することである。

またセトウチマイマイのスフィンゴ脂質の合成経路を考察するために、セラミド-Iと-IIの分子種とセラミドモノヘキソシド、スフィンゴリン脂質のセラミド部の分子種を比較した。

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〔報文〕 ジドデシルジメチルアンモニウム=ブロミドのベシクル による芳香族化合物の可溶化に及ぼす温度の影響

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ジドデシルジメチルアンモニウム=ブロミド (DDAB) ベシクル溶液中での芳香族化合物 (フェノール, 安息香酸, ベンゼン, エチルベンゼン) の可溶化に及ぼす温度の影響について, 可溶化平衡定数 (K_{vesicle}), ベシクル二分子膜の微視的粘性, ベシクルの対イオン解離度 (α) の測定等から検討した。ベンゼンおよびエチルベンゼンは温度が8℃以下の場合, ベシクルにはほとんど可溶化されなかったが, 8~10℃の温度範囲でこれらの溶質の K_{vesicle} 値は著しい増加を示した。蛍光測定よりベシクルの相転移温度 (T_c) は約9.5℃であることがわかった。このことから, ベンゼンおよびエチルベンゼンの可溶化はベシクル二分子膜の粘性に依存することがわかった。また, K_{vesicle} 値と芳香族溶質の *n*-ドデカン/水相間の分配係数 (K_{dodecane}) を比較したところ, エチルベンゼンはベシクル二分子膜の内部に可溶化されるが, ベンゼンの場合にはその π 電子と親水基カチオンとの間の相互作用によりベシクル表面近傍に可溶化されることが示唆された。一方, フェノール並びに安息香酸の K_{vesicle} 値はほぼ T_c で極大となり, α 値もまた T_c 付近で極大値を示した。このことから, フェノールと安息香酸の可溶化はベシクルの帯電の度合いに依存することが明らかとなった。すなわち, これらの極性溶質はその極性基と DDAB 親水基カチオンとの間の相互作用によりベシクル表面に可溶化されると考えられる。

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〔報文〕 高度不飽和リン脂質の自動酸化挙動 (第1報) 高度不飽和リン脂質を含む海産油の酸化安定性

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高度不飽和リン脂質に富む筋子油の自動酸化挙動をオキアミ油とサケ油の自動酸化挙動と比較した。筋子油とオキアミ油はカロテノイドの一種であるアスタキサンチンとリン脂質を含むため, 30℃の自動酸化に対してサケ油よりもはるかに安定であった。次に, 筋子油とそのトリアシルグリセリン及びリン脂質区分の酸化安定性を同条件下に評価した。

その結果, 筋子油中のヒドロペルオキシドの蓄積は筋子油に含まれるアスタキサンチンとトコフェロールの酸化防止効果により, トリアシルグリセリン区分やリン脂質区分中よりもかなり抑制された。