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[15] Crystal structure analysis of **1**:[16] $M_r = 9378.9$, monoclinic, space group $P2_1/n$, $Z = 2$, $a = 17.548(3)$, $b = 20.351(3)$, $c = 19.401(3)$ Å, $\beta = 90.98(2)$, $V = 6927.42$ Å^3, $\rho_{calcd} = 4.49\,g\,cm^{-3}$, $\mu_{Mo} = 274.2\,cm^{-1}$, crystal size $0.3 \times 0.3 \times 0.2$ mm^3, $2\theta_{max} = 50^\circ$, $Mo_{K\alpha}$ radiation, Nonius-CAD4 four-circle diffractometer, graphite monochromator, $\omega/2\theta$ scanning, $T = 293$ K, 15367 measured reflections, 12030 symmetry-independent reflections, 8358 reflections $> 2\sigma(I)$, absorption correction (psi scan, max./min. transmission 99.9/53.9%), isotropic extinction correction, 437 refined parameters (W, Cs anisotropic; O isotropic; no H atoms), residual electron density $< 6.9\,e\,Å^{-3}$, structure solution with direct methods (SHELXS-86) and difference Fourier techniques (XTAL 3.5), weighting $1/\sigma^2(F)$, $R = 0.076$ $(I > 2\sigma I)$, $Rw = 0.05$.

[16] Further details on the crystal structure investigation may be obtained from the Fachinformationszentrum Karlsruhe, D-76344 Eggenstein-Leopoldshafen, Germany (fax: (+49) 7247-808-666; e-mail: crysdata@fiz-karlsruhe.de), on quoting the depository numbers CSD-408188 (**1**) and CSD-408189 (**2**).

A Fullerene/Lipid Electrode Device: Reversible Electron Transfer Reaction of C_{60} Embedded in a Cast Film of an Artificial Ammonium Lipid on an Electrode in Aqueous Solution**

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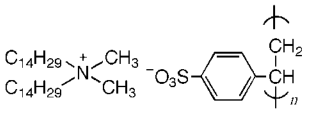
and Takamasa Sagara

The development of lipid bilayer modified electrodes whose structures mimic those of biomembranes is highly attractive, because such a study would produce a methodology for novel surface modification and functionalization. We and other have focused on the combination of fullerene chemistry and the chemistry of lipid bilayer membranes.[1] The goal in this study is to design and construct a system showing fast electron transfer reactions of fullerenes using lipid films as an electrode modifier. Fullerenes form multiply charged anions because of their high degrees of degeneracy of the LUMO, which lead to a variety of unique properties;[2, 3] however, the electrochemistry of fullerene thin films is rather complicated.[3, 4]

We describe here for the first time the discovery that C_{60} embedded in a cast film of an artificial lipid with multiple ion pair interactions (poly(ion-complexed) lipid)—namely, dimethylditetradecylammonium poly(styrene sulfonate) (**1**)—on an electrode undergoes two reversible electron transfer reactions with the underlying electrode in an aqueous solution. Furthermore, the generated radical monoanion and the dianion are very stable. To our knowledge, no report has been published thus far describing reversible electron transfer reactions of fullerene thin films on electrodes in an aqueous solution.[5] The poly(ion-complexed) lipid **1** used in this study is insoluble in water, but possesses fundamental characteristics of dispersed lipid bilayer membranes in an aqueous solution.[6] We also used cast films of the biological lipid dimyristoylphosphatidyl choline (**2**) as matrix films for comparison with **1**.



1

Compound **1** was synthesized according to the previously described method[7] and analyzed by IR and NMR spectroscopy as well as elemental analysis. This compound is readily soluble in benzene and can be used to form, by the conventional solvent evaporation method, multibilayer films. Lipid **2** was purchased from Sigma and used as received. Production

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and stability of the multiply charged anions of C_{60} (Bucky USA, 99.995%) were examined with the electrochemical method. Modified electrodes were prepared by the following procedure: A portion (10 μL) of C_{60}/**1** or C_{60}/**2** in benzene ([**1**] = [**2**] = 15.2 mM, [C_{60}] = 0.80 mM) was placed on a homemade basal plane pyrolytic graphite (BPG) disk electrode[6] (area 0.20 cm^2) and then dried under air. The electrochemical properties of the cast films on the BPG electrode was examined at 25 °C with cyclic voltammetry (BAS-100BW Electrochemical Analyzer, Bioanalytical Systems) under an argon atmosphere. A Ag/AgCl/saturated KCl electrode and a Pt plate electrode were used as the reference and the counter electrodes, respectively.

The electrogenerated C_{60} radical monoanion at the electrode modified with C_{60} alone in the aqueous system has been reported to be unstable; that is, the voltammetric response disappears after several cyclic potential scans.[8] Szucs and coworkers[9] observed a reduction current for fullerene films on an electrode in an alkaline aqueous solution, but the electrochemistry was completely irreversible. The fullerene C_{60} incorporated in a cast film of the biological lipid **2** on an electrode did not communicate with the underlying electrode; that is, no faradaic current was observed for a C_{60}/**2**-modified electrode (data not shown). In contrast, C_{60}/**1**-modified electrodes gave quite different results. Figure 1 shows typical cyclic voltammograms (CVs) for a cast film of C_{60}/**1** on BPG. There are two reversible redox couples at formal potentials of −290 and −910 mV. The behavior of both couples did not change even after 50 cycles. The cathodic and anodic peak currents for C_{60} increased in proportion to the square root of the scan rates in the range of 5–500 mV s^{-1} (data not shown), indicating that the electrochemistry is diffusion-controlled.[10]

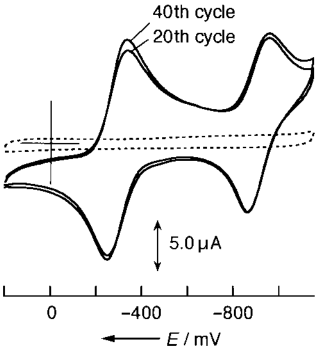

Figure 1. Cyclic voltammograms for cast films of **1** (dotted line) and C_{60}/**1** (solid lines) on electrodes in water. Supporting electrolyte: 0.5 M tetraethylammonium chloride, reference electrode: Ag/AgCl/saturated KCl, scan rate: 100 mV s^{-1}.

The amount of C_{60} that has reacted, as calculated from the CV of the C_{60}/**1**-modified electrode at a very low scan rate (2 mV s^{-1}), was 2.6×10^{-9} mol cm^{-2} [11] (average for four films). This corresponds to a coverage of about 17 monolayers of C_{60} or about 180 monolayers of C_{60}/**1** (assuming cross-sectional areas of 1.0 and 0.5 nm^2 for C_{60}[12] and **1**, respectively). This result indicates that the fullerene in the film is disposed in such a way that it can communicate electrochemically with the underlying electrode.

The further stability of the electrogenerated radical monoanion and the dianion of C_{60} in this system was examined by the potential hold experiment. As shown in Figure 2, the radical monoanion is unusually stable; that is, virtually no change in the CVs for the first redox wave was observed even after holding the potential for 90 min at −600 mV. A hold of several minutes at −1150 mV, where the fullerene is present as a dianion, did not affect the CVs, but longer holds caused a gradual decrease in the current. This suggests irreversible decomposition of the C_{60} dianion and/or dissolution of the C_{60} dianion into the bulk solution.

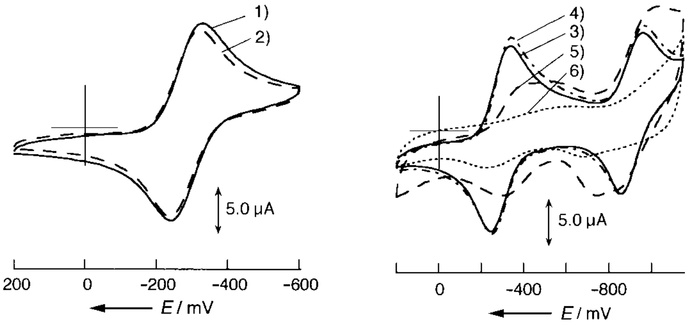

Figure 2. Effect of holding the potential for various lengths of time in the measurement of the cyclic voltammograms for a cast film of C_{60}/**1**. Hold time: 1) and 3): 0 min; 2) 90 min at −600 mV; 4) 1.5 min at −1150 mV; 5) 16.5 min at −1150 mV; 6) 61.5 min at −1150 mV. Supporting electrolyte, 0.5 M tetraethylammonium chloride, reference electrode: Ag/AgCl/saturated KCl, scan rate: 100 mV s^{-1}.

Since the electrochemical reduction of cast films of C_{60} involves incorporation of cations, supporting electrolytes are known to influence the voltammograms.[13, 14] In our system, however, the CVs for cast films of C_{60}/**1** on BPG were essentially the same in 0.5 M aqueous solutions of NaCl, KCl, and $CaCl_2$ (data not shown). Taken together with the result for the C_{60}/**2**-modified electrode, this indicates that these electrolyte cations are not major counterions of the fullerene radical monoanion and of the fullerene dianion. Instead, the dimethylditetradecylammonium cation in **1** may act as the counterion during the reduction of the fullerenes.[15]

In conclusion, we have designed and constructed a fullerene/lipid device which shows stable and reversible electron transfer reactions of C_{60} with the electrode. Our finding would be applicable to a variety of fullerene derivatives, higher fullerenes, and metallofullerenes.

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[10] The peak separations between the cathodic and the anodic waves were 62 ± 3 mV. The electrochemistry of our system is governed by the diffusion of C_{60} and/or the electrolytes, and/or by electron hopping (self-exchange electron transfer between C_{60} molecules in the film).

[11] The total amount of electroactive C_{60} in the film should be greater than this because the redox reaction at a scan rate of $2\,mV\,s^{-1}$ still involves diffusing species.

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[15] The charge balance is maintained by incorporation of cations from the bulk solution.

Direct NMR Spectroscopic Observation of a Lanthanide-Coordinated Water Molecule whose Exchange Rate Is Dependent on the Conformation of the Complexes

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The development of magnetic resonance imaging (MRI) techniques for medical diagnosis has been accompanied by an explosive growth of interest in the study of water-soluble, paramagnetic metal complexes as contrast agents.[1] The contrast agents markedly improve the image contrast by enhancing the nuclear magnetic relaxation rates of the water protons in the tissues where they are distributed. The agents currently used in clinical practice are chelates of the Gd^{III} ion, which is particularly suitable because of its high magnetic moment and long electronic relaxation time (T_{1e}). The mechanism of the relaxation enhancement involves the modulation of the dipolar interaction between the magnetic moment of the electrons in Gd^{III} ions and the nuclear spins of the water protons in the inner and outer coordination sphere of the complex.[1, 2] The efficiency of the process depends primarily on the number q of water molecules bound to the metal ion, their exchange rate (k_{ex}) with the bulk water, and the rate of molecular reorientation. The residence lifetime τ_M ($\tau_M = 1/k_{ex}$) plays a particularly important role since it contributes directly to the modulation of the electron–nucleus dipolar interaction, and it controls the efficiency of the transfer of the paramagnetic effect to the bulk water. Thus, the issue of the water exchange rate in lanthanide(III) complexes is of paramount importance in the development of novel contrast agents for MRI. In fact, in a number of Gd^{III} chelates with $q = 1$ τ_M is much longer than that found for Ln^{III} aquo ions, which is of the order of nanoseconds,[3] and it may limit the relaxation efficiency of the contrast agents.[4]

Among the different complexes used as contrast agents for MRI, $[Gd(dota)]^-$ (dota = 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid) should be the candidate of choice because of its high thermodynamic and kinetic stability. The long electronic relaxation time of the Gd^{III} ion prevents the observation of the NMR spectra of its complexes, and its solution structure had to be inferred from the ^1H and ^{13}C NMR spectra of the related complex $[Eu(dota)]^-$. As previously reported, $[Eu(dota)]^-$ consists of a pair of isomers, namely, **M** and **m**, endowed with the same square [3333] conformation of the macrocyclic ring, but with a different layout of the acetate arms. This difference results in a square antiprismatic and a twisted antiprismatic geometry for **M** and **m**, respectively (see Scheme 1).[5] The two isomers are in slow exchange near room temperature and yield two distinct sets of six resonances in the ^1H NMR spectrum for the C_4-symmetric ring and the diastereotopic CH_2CO protons. The resonance of the coordinated water molecule has not been observed (nor in other $[Ln(dota)]^-$ chelates) because its exchange rate is too fast on the NMR time scale ($k_{ex} = 4.1 \times 10^6\,s^{-1}$ at 298 K, as inferred from ^{17}O NMR data on $[Gd(dota)]^-$).[6] Recently, we reported that a Gd^{III} complex with a dota-like ligand containing four *N*-methylcarboxamide groups in place of the four carboxylate groups displays a large increase in the residence lifetime of the coordinated water molecule.[7] The slow exchange rate is a consequence of the stronger $Gd-OH_2$ interaction and a stabilizing hydrogen-bonding interaction to the proximate anions. The slow exchange of the coordinated water in this type of complex may give further insight into the relationship between the solution structure of the Ln^{III} chelate complex and the water exchange rate.

Here we have considered the Eu^{III} complex with the macrocyclic ligand dotam (dotam = 1,4,7,10-tetrakis(carbamoylmethyl)-1,4,7,10-tetraazacyclododecane). Figure 1 shows the ^1H NMR spectrum of $[Eu(dotam)]^{3+}$ in CD_3CN at 232 K. The compound is present as a mixture of **M** and **m** isomers whose ^1H chemical shifts are similar to those reported for the parent complex $[Eu(dota)]^-$ (Scheme 1). A 2D-EXSY NMR experiment carried out at 274 K in D_2O confirmed this analogy, and enabled the resonances to be assigned.[5b] In addition to the expected set of ligand resonances, an extra resonance for each isomer (of relative intensity two) is found at $\delta = 84.11$ (**M** isomer) and $\delta = 19.03$ (**m** isomer), respectively, which are assigned to the water molecules coordinated to

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