Title	STUDIES ON ELECTRON-TRANSFER REACTIONS IN ALCOHOL INDUCED BY A PHOTOREDOX SYSTEM OF EuIII/EuII AND BY IONIZING RADIATION : APPLICATION FOR ORGANIC SYNTHESIS.
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STUDIES ON ELECTRON-TRANSFER REACTIONS IN ALCOHOL INDUCED BY A PHOTOREDOX SYSTEM OF Eu^{III}/Eu^{II} AND BY IONIZING RADIATION: APPLICATION FOR ORGANIC SYNTHESIS.

（アルコール中のEu^{III}/Eu^{II} 光レドックス系および電離性放射線により誘起される電子移動反応に関する研究 ： その有機合成への応用）

1986

AKITO ISHIDA

Preface

The work of this thesis was performed under the guidance of professor Setsuo Takamuku at the Institute of Scientific and Industrial Research, Osaka University.

The object of this thesis is to develop the photoredox reactions and also organic radiation chemistry.

The author hopes that his findings described in this thesis contribute to the development of organic photochemistry and also radiation chemistry.

A Ishida

Akito Ishida

Ibaraki, Osaka

January, 1986

List of Papers

The contents of this thesis are composed of the following papers.

1) Photochemical Reactions of α-Methylstyrene Induced by Eu^{III}/Eu^{II} Photoredox System in Methanol
A. Ishida, S. Toki, and S. Takamuku
Chem. Lett., **1985**, 893.

2) Hydroxymethylation of 1,3-Dimethyluracil and Its Derivatives Induced by a Photoredox System of Eu^{III}/Eu^{II} in MeOH.
A. Ishida, S. Toki, and S. Takamuku
J. Chem. Soc., Chem. Commun., **1985**, 1481.

3) Radiation Induced Reactions of 1,3-Dimethyluracil and Its Derivatives with Alcohols - Comparison with the Photoredox Reactions
A. Ishida, S. Toki, and S. Takamuku
Radiat. Phys. Chem., **1986**, in press.

4) Fluorescence Quenching Study of Eu^{II}-Crown Complexes by 5-Substituted-1,3-Dimethyluracils
A. Ishida, S. Toki, and S. Takamuku
Chem. Lett., **1986**, in press.

5) Photochemical Hydroxymethylation of Alicyclic and Aliphatic Alkenes Induced by a Eu^{III}/Eu^{II} Photoredox System in Methanol
A. Ishida, S. Yamashita, S. Toki, and S. Takamuku
Bull. Chem. Soc. Jpn., in contribution.

6) One-Electron Reduction of Uracil and Its 5-Substituted Derivatives - Pulse Radiolytic Study in Organic Media
A. Ishida, S. Toki, and S. Takamuku
in preparation.

7) The Reactions of Malonic Ester Induced by a Photoredox System of Eu^{III}/Eu^{II} in Alcohols
A. Ishida, S. Yamashita, S. Toki, Y. Okamoto, and S. Takamuku
in preparation.

Supplementary Papers

8) Electron-Transfer Reactions Induced by Ionizing Radiation and Photoirradiation : Its Application for Organic Synthesis
A. Ishida, S. Toki, and S. Takamuku
Mem. Inst. Sci. Ind. Res., Osaka Univ., **43** (1986) in press.

9) Photoreductive Dimerization of Styrenes and Hydrogen Formation by a Redox Reaction of Europium Ion in Methanol
A. Ishida, S. Toki, and S. Takamuku
Proc. The Fifth International Conference on Photochemical Conversion and Storage of Solar Energy, 1984, Osaka, p. 312.

10) Photoredox Reaction of Eu^{III}/Eu^{II} in Alcohol - Reduction of Nucleobase by Eu^{II} and Effects of Crown Ethers

A. Ishida, S. Toki, and S. Takamuku

Proc. XIIth International Conference on Photochemistry, 1985, Tokyo, p. 553.

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2-3 Reactions of Dialkyl Malonates and Its Derivatives

2-4 Reactions of 1,3-Dimethyluracil and Its Derivatives

Chapter 3. One-Electron Reduction of Uracil and Its Derivatives Induced by Ionizing Radiation

3-1 One-Electron Reduction of 1,3-Dimethyluracil and Its Derivatives Induced by γ-Irradiation

Introduction

In recent years, the requirements of the chemical conversion and storage of solar energy have made the photo electron transfer reactions attractive. Many photoredox reactions have been reported. Most of them consist of a photosensitizer, a sacrificial electron donor or acceptor, and a reaction substrate. The following properties are required for the photosensitizer; appropreite redox potentials, an appropriate absorption spectrum, a long lifetime of the excited state, a stability, and etc. Metal complexes have been used favorably because of their excellent redox properties and visible absorptions. However, for synthetic applications, the stability is more significant than the visible absorptions. On the other hand, these photoredox systems have an essential disadvantage to form by-products derived from the sacrificial components.

With these views, the author has investigated a novel type of synthetic photoredox reactions by use of europium ions as photosensitizers.

The charge separation occurres initially in the photoredox system and the similar state can be produced easily by irradiation of ionizing radiation. The author has also investigated the reactions induced by ionizing radiation and attempted the comparison with the photoredox reactions.

Chapter 1 deals with the hydrogen evolution from alcohols by use of a Eu^{III}/Eu^{II} photoredox system. The CT-excitation mechanism and the effect of anion will be discussed.

Chapter 2 deals with the synthetic applications of Eu^{III}/Eu^{II} photoredox system by use of various substrates, aromatic alkenes, alicyclic and aliphatic alkenes, esters, and uracil derivatives. The characteristic reaction mechanisms depending on the substrates will be discussed.

Chapter 3 deals with the one-electron reduction of uracil and its derivatives. The synthetic reactions by γ-irradiation and the pulse radiolysis study will be discussed.

Chapter 4 deals with the fluorescence quenching study of Eu^{II} by uracil derivatives. The fluorescence of Eu^{II} is known to be enhanced by the aid of crown ethers. The correlation of the quenching behavior and the reaction mechanism suggested in Chapter 2 will be discussed.

Chapter 1. Eu^{III}/Eu^{II} Photoredox System in Organic Solvents

Abstract

The photoredox reaction by use of Eu ion was investigated in organic solvents. On illumination of a methanol solution of $EuCl_3$ through a Pyrex filter, oxidation of a methanol occurs along with formation of Eu^{II} ion. Thereafter, Eu^{II} becomes the main light-absorbing species and promotes hydrogen evolution. This system showed a very high turnover number.

Introduction

Many synthetic photoredox reactions have been reported in which aromatic hydrocarbons, dyes, metal complexes, and metal ions are used as photosensitizers. The photosensitizer must have following poperties in order to design an efficient redox system; an appropriate redox potential, a long lifetime of the excited state, an appropriate absorption spectrum, stability, and etc. Recently, metal complexes have been favorably used as a photoredox sensitizer because of their excellent properties.1) However, synthetic photoredox system requires stability and reproducibility rather than the absorption of visible light. There have been only a few reports of photoredox reactions which are sensitized by transition metal ions2) because of their unsuitable redox potentials in spite of the stabilities.

Photochmical reactions of lanthanide ions in homogeneous solutions are attracting much attention as efficient photoredox systems for harnessing solar energy and also for chemical synthetic processes since they have several stable oxidation states.3) For example, an aqueous solution of Eu^{III} undergoes photoredox reactions by 254 nm irradiation, in which Eu^{II} and OH radical are formed.4) In the presence of a radical interceptor such as 2-propanol, hydrogen evolution becomes a main process which can be induced by further photochemical reactions of Eu^{II}.5) However, photochemical studies of lanthanide ions are rather limited to aqueous systems of simple ligand molecules6) and in organic solvent there are only a few reports relating to the quenching of the photoexcited aromatic hydrocarbons.7) In this work, an excellent photoredox character of Eu ion in organic solvent was observed.

Results and Discussion

A methanol solution of $EuCl_3$ $6H_2O$ was saturated with Ar and filled in a Pyrex cell which connected with a gas syringe and irradiated with a high pressure mercyry lamp. The irradiation resulted in the formation of hydrogen gas and rather small amount of ethyleneglycol as shown in Fig. 1. Formaldehyde was also detected by the reaction of 2,4-dinitrophenylhydrazine. Similar hydrogen evolution was also observed in ethanol(EtOH), 2-propanol(2-PrOH), and tetrahydrofuran(THF) solution, but in 2-PrOH and THF solution white precipitates were separated out by irradiation. EtOH solution provided about 4 times amount of hydrogen than that of a methanol solution as shown in Fig. 2. The turnover number reached 1000 at 120 h irradiation of a MeOH solution ($EuCl_3$: 1 mmol dm^{-3}).

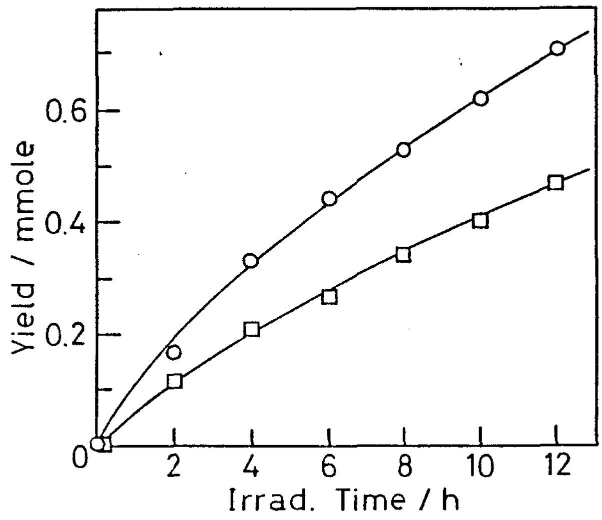


Fig. 1. Yields of hydrogen (—○—) and ethylene glycol (—□—) vs. time plot for the photoreaction of 5 mmol dm^{-3} solution of $EuCl_3$ 5 mL of methanol.

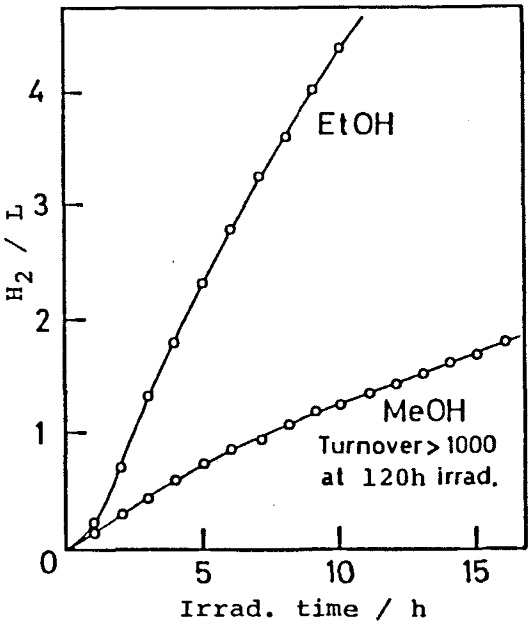


Fig. 2. Hydrogen evolution from alcohol solution of $EuCl_3$. [$EuCl_3$ $6H_2O$]=1 mmol dm^{-3}, 450 mL, Ar saturated, Pyrex cell.

In aqueous solutions, it was reported that no hydrogen evolution was observed by the irradiation through a Pyrex filter.[5)] The absorption spectra of a methanol solution of $EuCl_3$ before and after the irradiation are shown in Fig. 3.

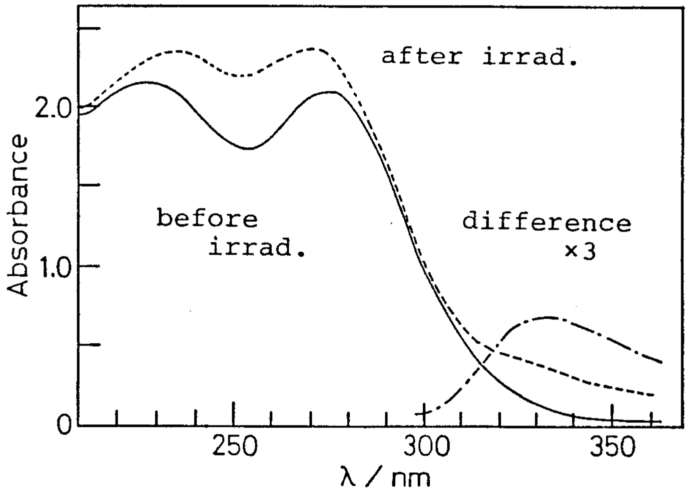
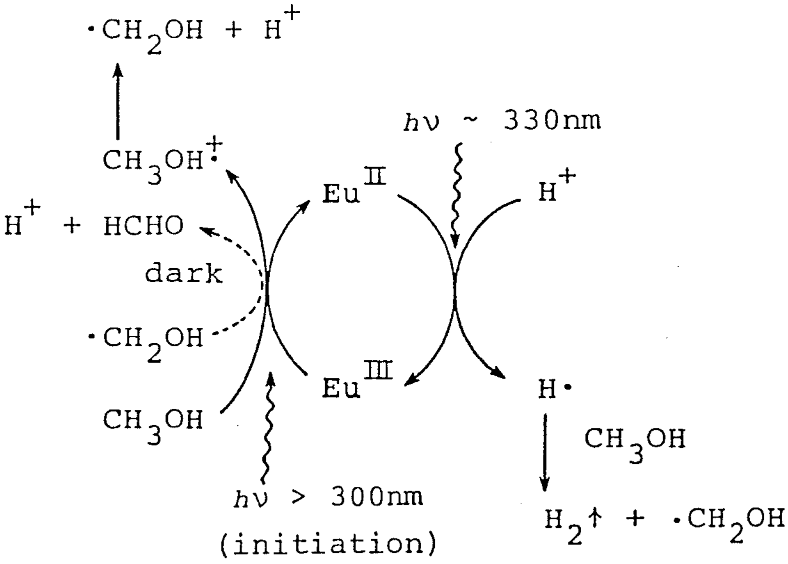


Fig. 3. Absorption spectra of a methanol solution of $EuCl_3$ before and after irradiation. [$EuCl_3$ $6H_2O$]=5 mmol dm^{-3}, Ar saturated, Pyrex filter. ——: before, ---: after 8 h irrad., -·-·: difference spectrum enlarged by a factor of 3.

There are two absorption maxima at 230 and 275 nm. The latter absorption was not observed in an aqueous solution and assigned as a charge-transfer band between Eu^{III} and methanol because it disappeared by the addition of H_2O or aliphatic amines which can correlate with Eu^{III}. After the irradiation, a new absorption maximum was observed at 330 nm and assigned as Eu^{II}

because it disappeared by the addition of oxygen to the irradiated solution.[5)] Therefore, hydrogen evolution in this system is induced by the CT-excitation of Eu^{III}-MeOH initially and also by the excitation of Eu^{II} once formed. The amounts of Eu^{III} and Eu^{II} came to photostationary state after about 15 minutes irradiation.

On the basis of these experimental observation, the mechanism of hydrogen evolution was proposed to be as shown in Scheme 1.



Scheme 1.

Ethyleneglycol was produced by the coupling of hydroxymethyl radicals produced by the oxidation process and/or hydrogen abstraction process. Hydroxyalkyl radical can reduce Eu^{III} (see Table 1.)[8,9)] and this path was confirmed in an aqueous system[5)] but in the present case, however, the path seems to be not so important since the formation of ethyleneglycol was observed as shown in Fig. 1.

Table 1. Redox potentials of Eu ions and some radicals.

Species	E^0/V vs. NHE	
Eu^{III}/Eu^{II}	-0.43 - -0.38	a), b)
CH_2OH	-0.73	c)
CH_3CHOH	-0.69	c)
$(CH_3)_2COH$	-0.73	c)
$Eu^{III}/{}^*Eu^{II}$	-2.4	d)

a) M. Chou, C. Creutz, N. Sutin, J. Am. Chem. Soc., 99, 5615 (1977).
b) H. N. McCoy, J. Am. Chem. Soc., 58, 1577 (1936).
c) P. S. Rao and E. Hayon, J. Am. Chem. Soc., 96, 1287 (1974).
d) C. Creutz, Inorg. Chem., 17, 1046 (1978).

Photoirradiation was carried out on solutions of other Eu salts. $Eu(NO_3)_3$ has a strong absorption in the region of <270 nm (Fig. 4) but no hydrogen evolution was observed. In the case of $Eu(ClO_4)_3$ hydrogen was formed after the induction period. After the irradiation, the absorption spectrum changed to a similar one in the shape to that of $EuCl_3$ (Fig. 4). Therefore, the degradation of ClO_4^- by the irradiation was suggested.

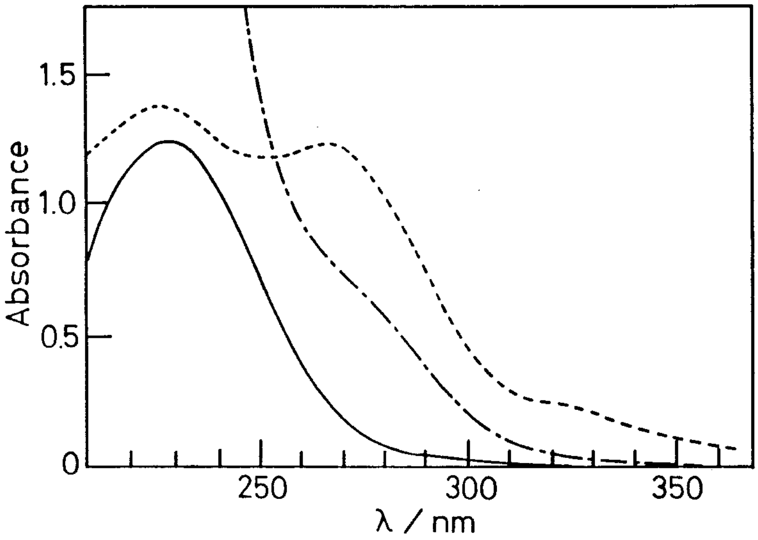


Fig. 4. Absorption spectra of methanol solutions of $Eu(ClO_4)_3$ and $Eu(NO_3)_3$ before and after 8 h irradiation.
[Eu salt]=2 mmol dm^{-3}, Ar saturated, Pyrex filter.

——: ClO_4^- before irrad.

- - -: ClO_4^- after irrad.

—·—: NO_3^- before and after irrad.

Experimental

Instruments

Photoirradiations were carried out with a Pyrex cell (5 mL or 180 mL or 450 mL) connected to a gas syringe and a 350 W high pressure mercury lamp. For measurement of absorption spectra, a 1 cm x 1 cm rectangular Suprasil cell and a Pyrex filter were used. Absorption spectra were recorded on Hitachi 323 spectrophotometer. GLC analyses were carried out on Shimadzu GC-7A gas chromatograph with 40 cm glass column packed with Porpak Type T or Qs. Sonications were carried out with a BRANSONIC B-32H ultrasonic cleaner.

Materials

$EuCl_3$ $6H_2O$, $Eu(ClO_4)_3$, and $Eu(NO_3)_3$ are used without further purification. Methanol, ethanol, 2-propanol, and tetrahydrofuran were distilled over CaH_2 prior to use.

Procedure

A reaction mixture was filled in the irradiation cell connected to a gas syringe and degassed by sonication for 10 minutes and saturated with Ar by bubbling for 10 minutes. After irradiation, a reaction mixture was sonicated for 5 minutes and volume of hydrogen was measured.

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Chapter 2. Synthetic Application of a Eu^{III}/Eu^{II} Photoredox System in Organic Solvents.

Introduction

Many synthetic photoredox reactions have been reported, however, they require an amine or a nitrile as a sacrificial electron donor and acceptor, respectively and these sacrificial components lowers the products yields by adducts formation. The organic sensitizer such a dye also induces adducts formation. Therefore, in these systems, no simple and clean reaction was expected essentially.

The Eu^{III}/Eu^{II} photoredox system in alcohols provides hydrogen atom, hydroxyalkyl radicals, and photoexcited Eu^{II} as reactive species. In this system, Eu ion and methanol act as a photosensitizer and an electron donor, respectively and Eu ion is very stable and provides high turnover as shown in the previous chapter. Therefore, by use of these species, effective synthetic photoredox reactions are expected.

In this chapter, it was presented the synthetic applications of Eu^{III}/Eu^{II} photoredox system by use of several substrates, aromatic alkenes (section 1), alicyclic and aliphatic alkenes (section 2), diesters of dicarboxylic acids (section 3), and nucleobases (section 4).

2-1 Reactions of Aromatic Alkenes

Abstract

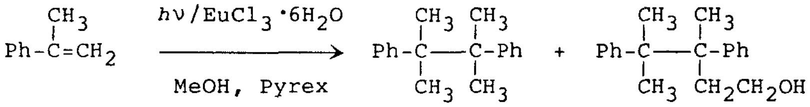
Photoirradiation of a methanol solution of α-methylstyrene and $EuCl_3$ $6H_2O$ with a Pyrex filter resulted in the formation of 2,3-dimethyl-2,3-diphenylbutane and 3,4-dimethyl-3,4-diphenylpentanol in high yields. Similar reactions were observed in other aromatic alkenes but the yields were rather low. This reaction was initiated by the excitation of Eu^{III}-CH_3OH CT-bands and followed by a successive photochemical reaction of Eu^{II} ions formed.

Introduction

In the previous chapter, it has been found that a photoredox system of Eu^{III}/Eu^{II} induces reduction of proton and oxidation of solvent. Since H atom and hydroxyalkyl radicals are formed as intermediates in this system, radical reactions are expected by the addition of alkene as a substrate. At first, reactions of some aromatic alkenes of which the reactivities have been studied widely and well known1) were investigated. In the course of the investigation, I have observed that the photoredox reaction of Eu^{III}/Eu^{II} in methanol induces an efficient reductive dimerization of styrenes competitively with hydrogen evolution upon illumination of light, $\lambda > 300$ nm.

Results and Discussion

Irradiation of a methanol solution of $EuCl_3$ $6H_2O$ (5 mmol dm^{-3}) by use of a high pressure mercury lamp and Pyrex filter resulted in the formation of hydrogen, ethyleneglycol, and formaldehyde. By the addition of α-methylstyrene (**1a**)(50 mmol dm^{-3}) to this system, the formation of hydrogen was reduced and the formation of 2,3-dimethyl-2,3-diphenylbutane (**2a**) and 3,4-dimethyl-3,4-diphenylpentanol (**3a**) was observed along with a small amount of cumene (5%), and 2-methyl-2-phenylpropanol (2%).



$$\underset{\textbf{1a}}{Ph\text{-}\overset{CH_3}{\overset{|}{C}}{=}CH_2} \xrightarrow[\text{MeOH, Pyrex}]{h\nu/EuCl_3\cdot 6H_2O} \underset{\textbf{2}\ \ 50\%}{Ph\text{-}\overset{CH_3}{\underset{CH_3}{C}}\text{—}\overset{CH_3}{\underset{CH_3}{C}}\text{-}Ph} + \underset{\textbf{3a}\ \ 24\%}{Ph\text{-}\overset{CH_3}{\underset{CH_3}{C}}\text{—}\overset{CH_3}{\underset{CH_2CH_2OH}{C}}\text{-}Ph} \quad (1)$$

1a 3 h, conv. 100% **2** 50% **3a** 24%

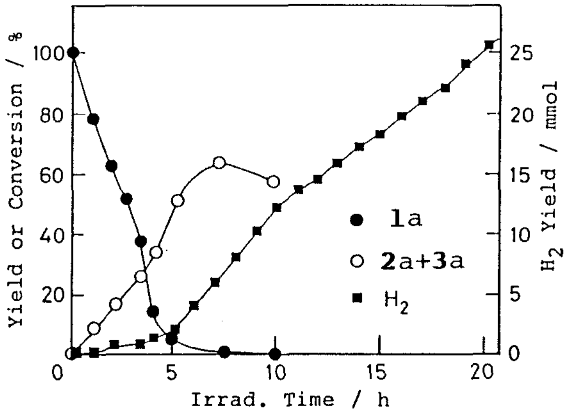


Fig. 1. Reaction of **1a** and hydrogen evolution as a function of irradiation time; [**1a**]=25 mmol dm^{-3}, [$EuCl_3$ $6H_2O$]=1 mmol dm^{-3} in 0.1 mL methanol, Ar saturated, Pyrex cell.

After the consumption of **1a**, hydrogen formation became predominant and the turnover number reached 250 at irradiation of 20 h as shown in Fig. 1.

These main products, 2a and **3a**, were isolated by column chromatography and characterized by IR, NMR, Mass, and elemental analyses. The formations of these products were not observed when the photolysis was carried out in acetonitrile nor in the absence of $EuCl_3$. Another important feature of this reaction is that the wavelength of the effective light is longer than 300 nm (through a Pyrex filter). Upon irradiation with 254 nm light which is effective for excitation of **1a**, the reaction did not occur. Similar reactions were observed in other aromatic alkene but the yields were rather lower than that of **1a** (see Table 1).

Table 1. Reaction of several aromatic alkenes in MeOH.[a)]

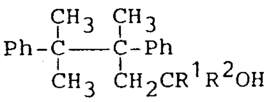
Substrate 1		Conv./%	Product yield/%[b)] Dihydrodimer 2	2:1 Adduct 3	Dihydromonomer 4	1:1 Adduct 5
α-methylstyrene	(1a)	100	50	24	5	1
styrene	(**1d**)	100	23	20	2	1
β-methylstyrene	(1e)	87	13	7	3	2
p-methylstyrene	(**1f**)	95	18	11	2	0
indene	(1g)	35	39	17	0	8
1,1-diphenyl-ethylene	(**1h**)	85	0	0	4	13, 15[c)]

a) Irradiation condition: $[EuCl_3\ 6H_2O]=5$ mmol dm^{-3}, $[1]=0.1$ mol dm^{-3}, in MeOH, 4 h irradiated with a high pressure mecury lamp through a Pyrex filter under Ar.

b) Yields are based on the amount of **1** consumed.

c) The yield of 5h'.

In order to get insight of this reaction, the effect of alcohols on the photolysis of the 1a-$EuCl_3$ system was examined. In the case of 2-propanol, $EuCl_3$ was hardly soluble, and after the irradiation a white precipitate separated out. Therefore, 20 vol% of methanol was added in order to increase the solubility for $EuCl_3$. The main products were a dihydro dimer of **1** (2), and a 2:1 adduct of **1** with the corresponding alcohol (3). The results are shown in Table 2.



$$\mathrm{Ph-\overset{CH_3}{\underset{CH_3}{C}}-\overset{CH_3}{\underset{CH_2CR^1R^2OH}{C}}-Ph}$$

3

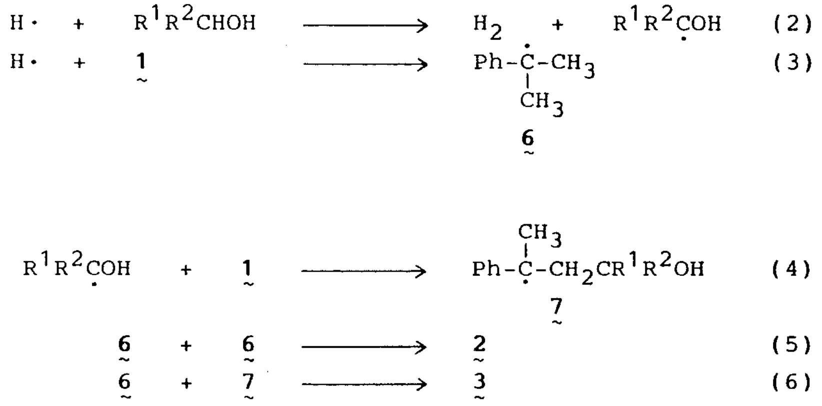
3a: $R^1=R^2=H$
3b: $R^1=H$, $R^2=CH_3$
3c: $R^1=R^2=CH_3$

Table 1. Product yields and selectivities in several alcohol[a)]

Alcohol	Product yield / % [b)] 2	 3	Product ratio 2 / 3	H_2 / dm^3
Methanol	50	24 (3a)	2.1	0.13
Ethanol	18	47 (3b)	0.4	0.50
2-Propanol[c)]	13	53 (3c)	0.2	0.53[d)]

a) Irradiation condition: $[EuCl_3 \cdot 6H_2O]=5$ $mmol \cdot dm^{-3}$, $[1a]=50$ $mmol \cdot dm^{-3}$, 3 h irradiation. b) Yields are based on the 1a consumed. c) 20 Vol% of methanol was added. d) For the mesurement of the hydrogen formation, methanol was not added.

The results in Table 2 are summarized as follows; i) the yields of 2a decreased in the order of methanol>ethanol>2-propanol, while the yields of adducts (3) and hydrogen formation increased in the order of methanol<ethanol<2-propanol, ii) total products yields were not influenced with alcohols (ca. 70%). These observations suggest a competitive reaction of hydrogen atoms, i.e., abstraction of hydrogen from alcohol leading to the formation of a hydrogen molecule and an α-hydroxyalkyl radical, and addition to **1**a as shown in Eqs. 2 and 3.



$$\mathrm{H\cdot} + \mathrm{R^1R^2CHOH} \longrightarrow \mathrm{H_2} + \mathrm{R^1R^2\dot{C}OH} \qquad (2)$$

$$\mathrm{H\cdot} + \underset{\sim}{\mathbf{1}} \longrightarrow \underset{\underset{\sim}{\mathbf{6}}}{\mathrm{Ph\text{-}\dot{C}(CH_3)\text{-}CH_3}} \qquad (3)$$

$$\mathrm{R^1R^2\dot{C}OH} + \underset{\sim}{\mathbf{1}} \longrightarrow \underset{\underset{\sim}{\mathbf{7}}}{\mathrm{Ph\text{-}\dot{C}(CH_3)\text{-}CH_2CR^1R^2OH}} \qquad (4)$$

$$\underset{\sim}{\mathbf{6}} + \underset{\sim}{\mathbf{6}} \longrightarrow \underset{\sim}{\mathbf{2}} \qquad (5)$$

$$\underset{\sim}{\mathbf{6}} + \underset{\sim}{\mathbf{7}} \longrightarrow \underset{\sim}{\mathbf{3}} \qquad (6)$$

These primary radicals undergo successive radical addition and radical-radical coupling reactions leading to the formation of the final products.

The present assumption, that the key intermediate for the final product formation is a hydrogen atom, is consistent with the fact that hydrogen evolution becomes a main and predominant path after 1a has been consumed. This assumption is also supported by the measurement of deuterium isotope effects on the present reactions using deuterated methanols, CD_3OH and CH_3OD. The experimental results can be summarized as follows: i) in the case of CD_3OH, no deuterium atom was incorporated in the product, **2a**, but two deuterium atoms are present in **3a** presumably at the alcoholic α-carbon atom on the basis of fragmentation pattern of the mass spectra, ii) in the case of CH_3OD, on the other hand, two deuterium atoms were incorporated in the product, 2a at C-1 and C-4 positions, and a deuterium atom in **3a** at C-5 position as shown in Table 3 and Table 4, iii) the product ratio, 2a/**3a**, did not vary with CD_3OH but decreased with CH_3OD as shown in Table 5.

Table 3. Mass spectra of the products irradiated in deuterated methanol.

Product	Solvent	Intensity of signal			
		238*	239	240	241
	CH_3OH	1	0.2	0.04	
2a	CD_3OH	1	0.28	0.04	
	CH_3OD	0.17	0.20	1	0.55
		268*	269	270	271
	CH_3OH	1	0.37	0.13	0.05
3a	CD_3OH		0.07	1	0.263
	CH_3OD	0.06	1	0.58	0.16

*: Parent ion in CH_3OH

[1a]=0.1 mol dm^{-3}, [$EuCl_3$]=5 mmol dm^{-3}, Ar sat.,
5 h irrad., Pyrex filter.

Table 4. Deuterium incorporation of the products.[a]

d	2a		3a	
	CD_3OH	CH_3OD	CD_3OH	CH_3OD
0	90.6%	13.0%	0%	4.8%
1	7.2	12.7	6.5	77.9
2	2.2	74.2	93.5	17.4
3	0	0	0	0

a) Calculated values on the basis of data in Table 3.

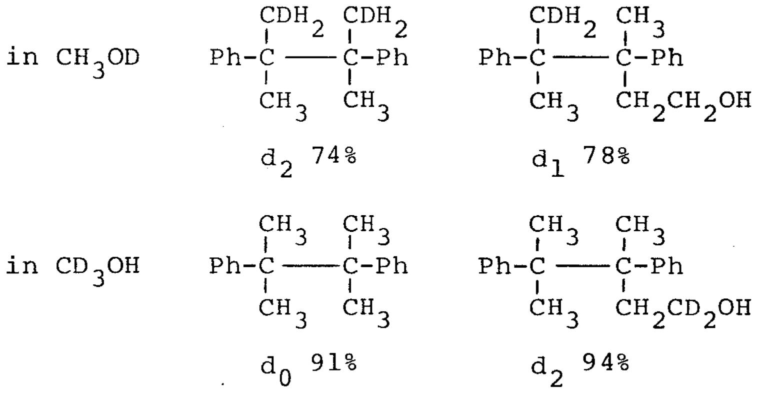
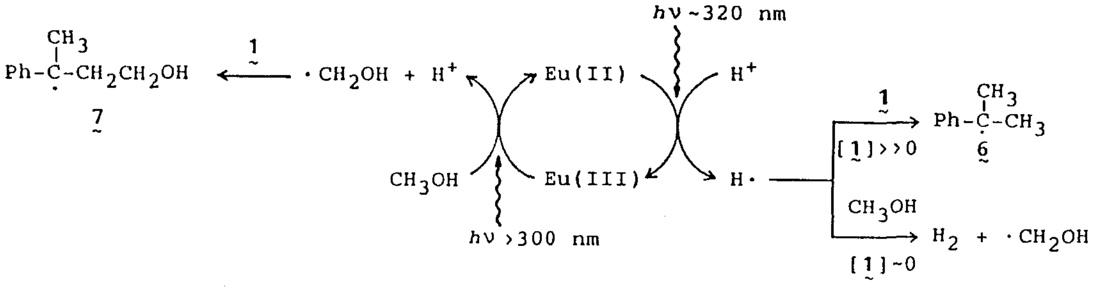


Table 5. Deuterium isotope effects [a]

Solvent	Product yield / % [b]		Product ratio
	2	**3a**	**2** / **3a**
CH_3OH	52	20	2.6
CD_3OH	42	17	2.5
CH_3OD	43	33	1.3

a) Irradiation conditions; $[EuCl_3 \cdot 6H_2O]$=5 mmol·dm^{-3}, [**1**]=100 mmol dm^{-3}, 5 h irradiation. b) Yields are based on the **1** consumed.

Important facts derived from these observations are; 1) hydrogen atoms presumed in Eqs. 2 and 3 originate from alcoholic hydrogen (MeOH), probably by the photochemical reduction by Eu^{II} ion, 2) in the case of CD_3OH, lack of deuterium isotope effect on the product ratio indicates that hydrogen abstraction from methanol (Eq. 2) does not compete with addition to 1a (Eq. 3). Therefore, the hydroxymethyl radical which results in the formation of 3a might be produced by another path, probably by the initial photochemical oxidation of methanol by Eu^{III} ion as mentioned below. Hydrogen abstraction from alcohol becomes, of course, an important path in ethanol and in 2-propanol on the basis of high yields of 3 and hydrogen molecules, 3) low product ratio, 2a/3a observed in CH_3OD might be caused by an increased rate constant of deuterium atom with methanol (Eq. 2) simply because of higher bond energy of HD than that of H_2.2) It is, however, difficult to conclude at present. On the basis of these experimental observations, the following rection scheme is presented.



Scheme 1.

The formation of Eu^{II} ions as the key active species for the reduction of **1a** was verified by the spectroscopic measurements. An absorption spectrum of methanol solution of $EuCl_3$ shows band maxima at 230 and 275 nm which are assigned to Eu^{III}-MeOH CT-band. After the irradiation of this solution in the presence of **1a**, new absorption band at 320 nm,$^{3)}$ which is due to Eu^{II} ion, was detected(Fig. 2). Emission spectrum of Eu^{II} was also observed at 446 nm by addition of 18-crown-6 ether after the irradiation (Fig. 3).$^{3)}$

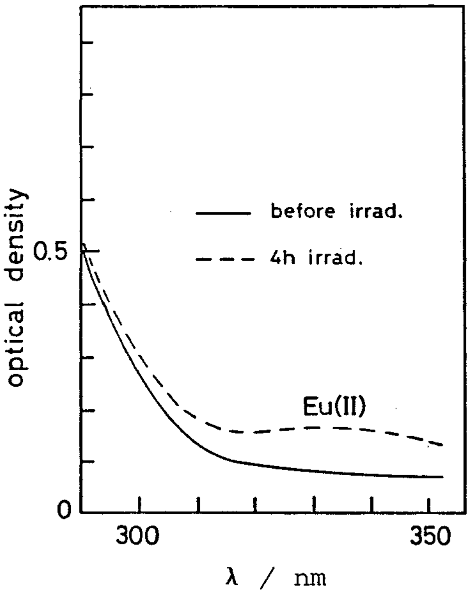


Fig. 2. Absorption spectra of a methanol solution of **1a** and $EuCl_3$ before and after 15 min irradiation.
[**1a**]=1 mmol dm^{-3}, [$EuCl_3$]=5 mmol dm^{-3}, Ar saturated, Pyrex filter.

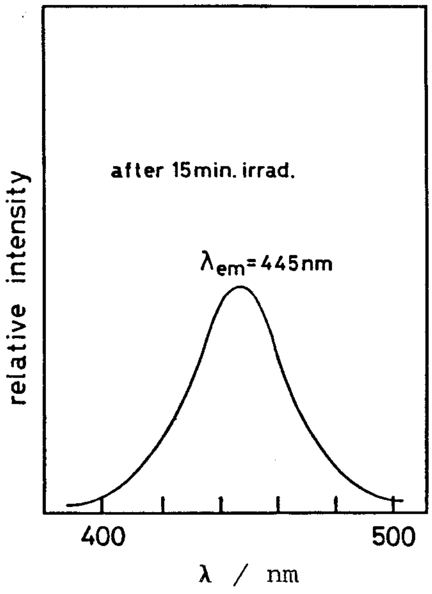


Fig. 3. Fluorescence spectra of a methanol solution of **1a** and $EuCl_3$ in the presence of 18-crown-6 ether after 15 min irradiation. [**1a**]=1 mmol dm^{-3}, [$EuCl_3$]=5 mmol dm^{-3}, [18-crown-6]=10 mmol dm^{-3}, Ar saturated, Pyrex filter.

Experimental

Instruments

GLC analyses were carried out on Shimadzu GC-7A gas chromatograph with 2 m glass column packed with OV-17. ^1H and ^{13}C NMR were recorded in $CDCl_3$ solution on Bruker WM-360 using TMS as an internal standard. Mass spectra were run on JEOL JMS-DX300 (GLC, EI, FAB Mass spectrometer) using the same columns as the GLC analysis. Absorption spectra were recorded on Hitachi 323 spectrophotometer. Fluoresence spectra were recorded on Hitachi 850 spectrofluorophotometer.

Photoirradiations were carried out with Pyrex cells (5 mL, 180 mL, 450 mL) connected to gas syringes with Teflon tubings, a high pressure mercury lamp, and a merry-go-round apparatus.

Materials

Aromatic alkenes obtained from TCI Co. were purified by distillation from sodium under reduced pressure prior to use. $EuCl_3$ was used without further purifications. Methanol, ethanol, and 2-propanol were distilled over CaH_2. Silica-gel for column chromatography was Kiselgel 60 (Merck Co.)

Procedure

Photoirradiation of an Alcohol Solution of $EuCl_3$ and Alkene

An alcohol solution of alkene (100 or 50 mmol dm^{-3}) and $EuCl_3$ was filled in a Pyrex cell connected to a gas syringe and degassed by sonication for 3 minutes and bubbled with Ar for 10 minutes and then irradiated with a 350 W high pressure mercury lamp at running water temperature.

Product Isolation

After the irradiation, the solvent was removed in vacuo and the residue was extracted with benzene to remove $EuCl_3$. The products were isolated by column chromatography on silica-gel eluted by benzene-hexane mixture. For elemental analysis, the alcohol adduct was acetylated with acetylchloride and p-dimethylaminopyridine.4)

Product Identification

2a; colorless needles(from $MeOH-H_2O$), mp 116 °C (lit mp 119 °C in Ref. 5); ^{1}H NMR($CDCl_3$) δ=1.26(s, 12H), and 6.93(bs, 10H); m/z 238(M^+), 119, 103, and 91.

3a; viscous oil, ^{1}H NMR($CDCl_3$) δ=1.29-1.30(s, 9H), 1.66(s, 1H), 1.84-1.93(m, 1H), 2.38-2.46(m, 1H), 3.23-3.49 (m, 2H), and 7.01-7.25(m, 10H); m/z 268(M^+), 149, 132, 119, 105, and 91; IR (neat) 3600, 3350, 1370, and 1030 cm^{-1}, Found: C, 81.24, H, 8.47%. Calcd for $C_{21}H_{26}O_2$(acetylated derivative of **3a**): C, 81.25, H, 8.44%.

5a; m/z 150(M^+), 119, 103, 91, 77, and 65.

3b; ^{1}H NMR (acetylated derivative of 3b, $CDCl_3$, $SiMe_4$) δ =1.05 (d, J=6.3 Hz, 2H), 1.11 (d, J=6.2 Hz, 3H), 1.27 (s, 3H), 1.29 (s, 6H), 1.68 (m, 1H), 7.15 (m, 10H); m/z 282(M^+), 267, 163, 145, 119, 103, 91, and 77; Found: C, 81.24, H, 8.71%.

Calcd for $C_{22}H_{38}O_2$(acetylated derivative of 3b): C, 81.44, H, 8.70%.

3c; ^{1}H NMR($CDCl_3$) (acetylated derivative of 3c) δ=1.00 (s, 3H), 1.11 (s, 3H), 1.24 (s, 9H), 1.59 (s, 1H), 1.63 (s, 1H), 1.89 (s, 3H), 6.95 (m, 10H); m/z 296(M^+), 281, 263, 223, 177, 159, 119, 105, 91, and 59; Found: C, 81.38, H, 8.78%. Calcd for $C_{23}H_{40}O_2$(acetylated derivative of 3c): C, 81.61, H, 8.93%.

The following products were identified by the mass spectra.

2d: m/z 210(M^+), 105, 91, and 77.

3d:m/z 240(M^+), 222, 178, 165, 152, 135, 134, 117, 115, 104, 91, and 77.

5d: m/z 136(M^+), 105, 91, 77, and 63.

2e: m/z 238(M^+), 119, and 91.

3e: m/z 268(M^+), 149, 131, 119, and 91.

4e: m/z 120(M^+), 91, 78, and 65.

2f: m/z 238(M^+), 119, 104, 91, 77, and 53.

3f: m/z 268(M^+), 149, 119, 105, and 91.

2g: m/z 234(M^+), 117, and 91.

3g: m/z 264(M^+), 147, 117, and 91.

5g: m/z 148(M^+), 130, 115, 91, and 31.

5h: m/z 212(M^+), 197, 135, 77, and 51.

5h':m/z 212(M^+), 194, 165, 115, 103, 91, 77, 51, and 31.

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2-2 Reactions of Alicyclic and Aliphatic Alkenes

Abstract

Photoirradiation of a methanol slution of $EuCl_3$ and alkene such as cyclohexene, cyclooctene, cyclododecene, and tetramethylethylene affords hydroxymethylalkene. Dihydrodimer of alkene, hydrogen, and ethyleneglycol are also formed. The reactions proceed via a radical mechanism induced by hydrogen atom and hydroxymethyl radical, which are produced by a photoredox reaction of Eu^{III}/Eu^{II} in methanol.

Introduction

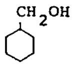
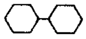
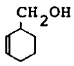
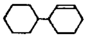
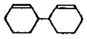
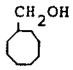
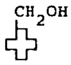
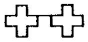
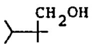
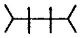
In the previous section (**2-1**), it has been presented a photoredox reaction of Eu^{III}/Eu^{II} in the presence of some aromatic alkenes in which hydrogen atom and a hydroxyalkyl radical added to the olefinic substrate and provided the products However, these radical species can induce hydrogen abstraction from solvent and the substrate. In this section, the reactions of some alicyclic and aliphatic alkenes induced by a Eu^{III}/Eu^{II} photoredox system in methanol was investigated in order to extend the application of this reaction system.

Results and Discussion

A methanol solution of alkene (**1a-1d:** 100 mmol dm^{-3}) and $EuCl_3$ (5 mmol dm^{-3}) was irradiated under argon atmosphere at $\lambda > 300$ nm. The methanol adduct of **1** (2), and the dihydro dimer of **1** (3) were obtained as main products along with a large amount of hydrogen gas and ethyleneglycol. In the absence of $EuCl_3$, the alkene was recovered unchanged from methanol after the irradiation for 8 h.

4a, **5a**, and **6a** were obtained as minor products from cyclohexene (**1a**). In the case of tetramethylethylene (**1d**), **7d** was formed as one of the main products (see Table 1.).

Table 1. Reaction of several alicyclic and aliphatic alkenes in MeOH.$^{a)}$

Alkene	Concn. mmol dm^{-3}	Conv. /%	H_2	$(-CH_2OH)_2$	Product yield/%$^{b)}$ 2	3	4	5	6	7
										
	100	71	137	40	49	22	1	16	2	
1a	500	49	12	-$^{c)}$	3	7	2	15	15	
										
	100	78	128	23	52	25				
1b	500	50	12	-	8	31				
										
	100	64	250	-	42	36				
1c	300	43	55	-	7	61				
										
	100	81	44	-	37	4				26
1d	500	50	3	-	13	7				25

a) Irradiation condition: $[EuCl_3]$=5 mmol dm^{-3}, 5 mL Ar saturated methanol solution, 8 h irradiated.
b) Yields were based on the amount of **1** consumed.
c) Not determined.

The formation of these main products (2 and 3) is reasonably explained as the results of an efficient trapping of primarily formed radicals from methanol (H and CH_2OH, Reaction 1-7) by the alkene added (Reactions 8-12).

$$\mathrm{Eu^{III}\text{-}CH_3OH} \xrightarrow{h\nu} \mathrm{Eu^{II} + CH_3O\cdot + H^+} \qquad (1)$$

$$\mathrm{Eu^{II}} \xrightarrow{h\nu} \mathrm{{}^{*}Eu^{II}} \qquad (2)$$

$$\mathrm{{}^{*}Eu^{II} + H^+} \longrightarrow \mathrm{Eu^{III} + H\cdot} \qquad (3)$$

$$\mathrm{CH_3O\cdot + CH_3OH} \longrightarrow \mathrm{CH_3OH + \cdot CH_2OH} \qquad (4)$$

$$\mathrm{H\cdot + CH_3OH} \longrightarrow \mathrm{H_2 + \cdot CH_2OH} \qquad (5)$$

$$\mathrm{2\ \cdot CH_2OH} \longrightarrow \mathrm{HO(CH_2)_2OH} \qquad (6)$$

$$\mathrm{Eu^{III} + CH_2OH} \longrightarrow \mathrm{Eu^{II} + HCHO + H^+} \qquad (7)$$

$$\mathrm{H\cdot + 1} \longrightarrow \mathrm{\cdot RH} \qquad (8)$$

$$\mathrm{\cdot CH_2OH + 1} \longrightarrow \mathrm{\cdot RCH_2OH} \qquad (9)$$

$$\mathrm{2\ \cdot RH} \longrightarrow \mathrm{HR\text{-}RH} \qquad (10)$$

$$\mathrm{\cdot RCH_2OH} \xrightarrow{\mathrm{H}} \mathrm{HRCH_2OH} \qquad (11)$$

$$\mathrm{\cdot RH + CH_2OH} \longrightarrow \mathrm{HRCH_2OH} \qquad (12)$$

Where RH and $R\text{-}CH_2OH$ stand for -alkyl radical and -hydroxylmethylalkyl radical which are formed by the addition of H and hydroxymethyl radical to alkene, respectively. The addition of H to alkene (Reaction 8) is in competition with an abstraction of H from methanol (Reaction 5). These competitive processes depend on the concentration of the alkene used, and the product ratio (2/3) was found to be very sensitive to the concentration of alkene as shown in Fig. 1. At low concentration of the alkene, hydrogen atom mainly abstracts hydrogen from methanol producing hydrogen molecules and hydroxymethyl radical. Thus, main reaction becomes hydroxymethylation of the alkene. With increasing of the concentration of alkene, hydrogen atom addition to alkene becomes competitive and the yield of dihydrodimer **(3)** increases up to 61 % at 0.3 mol dm^{-3} in the case of cyclododecene **(1c)**. These results are also consistent with the estimation on the basis of the kinetic data reported.$^{1)}$

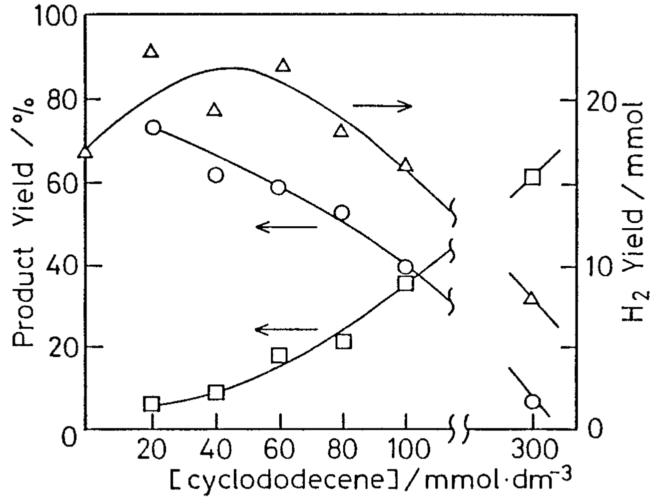


Fig. 1. Dependence of yields of hydrogen (—△—), **2c** (—○—), **3c** (—□—) on the concentration of **1c** for the photoreaction of EuCl$_3$ 6H$_2$O (5 mmol dm^{-3}) in methanol (5 mL) for 8 h.

The unsaturated products, **4a-6a** are considerably formed in the case of cyclohexene. It has been known that allylic hydrogens of cyclohexene are much more reactive toward abstraction than those of other alkenes. The fact was explained by the coplanarity of cyclohexenyl radical and was substantiated by the results reported by Mayo et al.[2] The ratios of k_{ab} (rate of H abstraction from alkene) to k'_{ad} (rate of addition to alkene) are 16, 0.4, 1.5, and 0.7 for cyclohexene, cyclooctene, cyclododecene, and tetramethylethylene, respectively. The unsaturated products (**4a**-**6a**) may be elucidated to be formed via the cyclohexenyl radicals.

$$(CH_3)_2\dot{C}CH(CH_3)_2$$

8d

In the case of tetramethylethylene, the reduction of **1d** took place to afford 2,3-dimethylbutane(**7d**). The radical **8d** formed by the addition of H to **1d** is a tertiary alkyl radical and the steric repulsion by an isopropyl and two methyl groups is anticipated to make the coupling reaction difficult. In t-butyl radical similar to **8d**, the disproportionation prevails much more over the coupling in solution, whereas in alicyclic alkyl radicals the former is inferior to the latter.[3] These suggest that the hydrogenation of alkene occurs mainly in tetrametylethylene, which is consistent with the experimental results.

In order to get an insight into this reaction, the experiments using deuterium-labelled compounds were carried out. The results are summarized in Table 2.

Europium chloride used containes 6 gram-equivalent H_2O as water of crystallization. However, its quantity is less than 0.1 wt% of the methanol and the effects of the water is presumed to be negligible. The yields of **2c** and 3c did not differ grately

Table 2. Deuterium isotope effects in photoreaction of $EuCl_3$ and cyclododecene (**1c**) in deuterated methanol.[a)]

Solvent	Product yield/%[b)] 2c	3c	Product ratio 2c/3c	H_2/mL
CH_3OH	59	19	3.1	17
CH_3OD	58	16	3.6	16
CD_3OH	21	28	0.75	14

a) $[EuCl_3]=5$ mmol dm^{-3}, $[\mathbf{1c}]=60$ mmol dm^{-3}, 2 mL Ar saturatd solution, 8 h irrad, Pyrex cell.

b) based on the amount of **1c** consumed.

in CH_3OH and CH_3OD. When CD_3OH was used, however, **2c** decreased significantly with an increase of **3c**. The evolution of hydrogen was also reduced in the case of CD_3OH. The initial processes, Reaction 1-3 are regarded to be not influenced by the deuterium labelling. A reaction for which deuterium isotope effects are expected is the hydrogen atom abstraction from methanol by hydrogen atom (Reaction 5) among the initial process. The retardation of Reaction 5 in CD_3OH, leads to the decrease of the yields of hydroxymethyl radical and also of hydrogen evolution with corresponding increases of cyclododecyl radical yields. These explanation is in accord with the experimental results in Table 2.

Concerning the hydrogen source for the formation of **2c** from β-hydroxymethylcyclododecyl radical **(9c)**, (Reaction 11) there are three possibilities: (i) recombination with hydrogen atom, (ii) disproportionation with other radicals, and (iii) abstraction of hydrogen from methanol. The first case seems to be not so important because the concentration of hydrogen atoms and the radical **9c** are very low. The second and the third cases are of some importance for the present reaction conditions. Especially, considering the dissociation energies of C-H bond in cyclohexane (402 kJ/mol)$^{4)}$ and C-H bond in methanol (394 kJ/mol),$^{5)}$ the hydrogen abstraction from methanol becomes more exothermic than that from cyclohexane by 8 kJ/mol. Therefore, for this process, deuterium isotope effect may contribute. This interpretation is in accord with the fact that in the case of styrene, a 2:1 styrene-methanol adduct and a dihydrodimer were obtained as the main products, but a 1:1 adduct was not detected. The benzyl type radical derived from styrenes can not abstract H from methanol, because the C-H bond energy of benzylic C-H bond is low, 356 kJ/mol. Therefore, the benzyl radical can only terminate by the coupling with another benzyl radical.

An example of photochemical hydroxymethylation is known for norbornene in which hydroxymethylation proceeds by a xylene-sensitization in methanol via a radical mechanism.$^{6)}$ On the contrary, cyclohexene and cycloheptene undergo dipolar addition of methanol to give methoxy products.$^{6)}$ The reactions are selective for cyclic six- and seven-membered rings. The present photoreactions of Eu-alkene systems in methanol are able to transform efficiently aliphatic and alicyclic alkenes to corresponding hydroxymethylalkanes, in which europium ion acts as an efficient sensitizer. Photoreaction of Eu^{III} and alkene in methanol is useful as a general synthetic method for the hydroxymethylation of alkenes.

Experimental

Instruments

GLC analyses were carried out on a Shimadzu GC-7A gas chromatograph with 2 m glass column (packed with OV-17) for cyclohexene, cyclooctene, and cyclododecene, with 40 cm glass column (packed with Porpak T or QS) for tetramethylethylene and ethyleneglycol.

^{1}H and ^{13}C NMR were recorded in $CDCl_3$ solution on a Bruker WM-360 spectrometer using TMS as an internal standard.

Mass spectra were run on a JEOL JMS-DX300 (GLC, EI, FAB Mass spectrometer) using the same columns as the GLC analysis.

Absorption spectra were recorded on a Hitachi 323 spectrophotometer. Fluoresence spectra were recorded on a Hitachi 850 spectrofluorophotometer.

Photoirradiations were carried out with Pyrex cells (5 mL, 180 mL, 450 mL) connected to gas syringes with Tefron tubings, a high pressure mercury lamp, and a merry-go round apparatus.

Materials

Aromatic alkenes were purified by distillation from sodium under reduced pressure prior to use. $EuCl_3$ was used without further purifications. Methanol, ethanol, and 2-propanol were distilled over CaH_2. Isotopically labelled methanols (Merck) were used without further purifications.

Procedure

Photoirradiation of an Alcohol Solution of $EuCl_3$ and Alkene

An alcohol solution of alkene (100 mmol dm^{-3}) and $EuCl_3$ (5 mmol dm^{-3}) was filled in a Pyrex cell connected to a gas syringe and saturated with Ar by bubbling for 10 minutes and then irradiated with a 350 W high pressure mercury lamp for 8 h at running water temperature. After the irradiation, the solution was concentrated under reduced pressure. The identification of products was carried out by direct comparison of GLC and Mass with those of available authetic samples. The following products were isolated by means of preparative gas chromatography (OV-17, 2 m) or by means of column chromatography on silica gel with hexane and benzene and identified by spectral data.

Identification of Products

2a; viscous oil; m/z (relative intensity) 96 (M^+-18, 7%), 83 (16), 81 (13), 67 (28), 55 (63), 41 (100), 39 (96), 31 (66).

4a; viscous oil; **4a** was transformed into **2a** by hydrogenation of the reaction solution mixture by palladium carbon; m/z (relative intensity) 94 (M^+-18, 2%), 81 (11), 79 (21), 66 (5), 53 (11), 41 (12), 39 (32), 31 (100).

3a, **5a**, and **6a**; An authentic sample of **6a** was obtained by photoreaction of 1a and benzophenone, and hydrogenated by palladium carbon to give new peaks coinciding with **3a** and **5a** at the early stage and concentrated to one peak (3a) after the end of the reaction.

3a; viscouse oil; m/z (relative intensity) 166 (M^+, 45%), 109 (19), 96 (29), 83 (97), 82 (100), 67 (90), 53 (39).

5a; m/z (relative intensity) 164 (M^+, 2%), 91 (13), 82 (22), 81 (54), 79 (72), 77 (35), 67 (24), 55 (100), 53 (54), 41 (94), 39 (81).

6a; m/z (relative intensity) 162 (M^+, 1%), 91 (11), 82 (7), 81 (100), 79 (89), 77 (43), 66 (20), 55 (22), 53 (51), 41 (92), 39 (69).

2b; ^1H NMR ($CDCl_3$, TMS) δ=1.33 (m, 14H), 1.83 (m, 1H), 2.47 (bs, 1H), 3.42 (d, J=6 Hz, 2H); 2,4-dinitrobenzoate of **2b**; mp 63-64°C; m/z (relative intensity) 336 (M^+, vw), 306 (3), 195 (12), 149 (13), 124 (15), 111 (21), 96 (100).

3b; colorless needle; mp 46-47 °C; m/z (relative intensity) 222 (M^+, vw), 111 (100), 110 (40), 82 (36), 69 (98), 55 (42), 41 (22); ^1H NMR ($CDCl_3$, TMS) δ=1.26-1.72 (m); ^{13}C NMR ($CDCl_3$, TMS, off-resonance) δ=44.5 (d), 30.9 (t), 27.0 (t).

2c; viscous oil; ^1H NMR ($CDCl_3$, TMS) δ=1.32 (m, 22H), 1.63 (t, J=6 Hz, 2H); m/z (relative intensity) 198 (M^+, vw), 180 (7), 166 (6), 152 (6), 137 (6), 123 (11), 111 (37), 97 (70), 83 (87), 69 (73), 55 (100); ^{13}C NMR ($CDCl_3$, TMS, off-resonance) δ=69.27 (t), 40.67 (d), 30.04 (t), 29.73 (t), 27.36 (t), 26.88 (t), 25.99 (t).

3c; needle mp 117-118 °C; m/z (relative intensity) 334 (M^+, 30), 166 (100), 111 (26), 97 (48), 96 (37), 83 (43), 82 (30), 69 (30), 55 (41); ^{13}C NMR ($CDCl_3$, TMS, off-resonance) 33.46 (d), 26.24 (t), 24.14 (t), 23.93 (t), 23.74 (t), 22.92 (t), 22.86 (t); Found: C, 86.14; H, 13.86%. Calcd. for $C_{24}H_{46}$: C, 86.13; H, 13.62%.

7d and **3d**; The structure of **7d** was identified by the direct comparison of GLC and Mass with those of authentic sample obtained by a hydrogenation of **1d**. **3d** was identified based on GLC-Mass data.

2d; viscous oil; ^1H NMR ($CDCl_3$, TMS) δ=0.82 (s, 6H), 0.85 (d, J=7 Hz, 6H), 1.64 (q, J=7 Hz, 1H), 1.90 (bs, 1H), 3.37 (s, 2H); ^{13}C NMR ($CDCl_3$, TMS, off-resonance) δ=17.40 (q), 30.00 (q), 32.65 (d), 37.36 (s), 70.92 (t).

References and Notes

1. Rate of addition of H atom to ethylene is 3.2×10^9 $mol^{-1}dm^3s^{-1}$ [J. K. Thomas, J. Phys. Chem., **71**, 1919 (1967)] and that of abstraction of H atom from methanol by H atom is 2.9×10^6 $mol^{-1}dm^3s^{-1}$ [P. Neta, G. R. Holden, and R. H. Schuler, J. Phys. Chem., **75**, 449 (1971)]. When the concentration of alkene is ca 0.02 mol dm^{-3} the reaction of addition and abstraction are suggested to be comparable.

2. F. R. Mayo, Acc. Chem. Res., 1, 193 (1968); D. E. Van Sickle, F. R. Mayo, and R. M. Arluck, J. Am. Chem. Soc., **87**, 4824 (1965).

3. M. J. Gibian, R. C. Corley, Chem. Rev., **73**, 441 (1973); R. A. Scheldon and J. K. Kochi, J. Am. Chem. Soc., **92**, 4395 (1970).

4. K. C. Ferguson and E. Whittle, Trans. Faraday Soc., **67**, 2618 (1976).

5. D. M. Golden, and S. W. Benson, Chem. Rev., **69**, 125 (1969).

6. P. J. Kropp, J. Am. Chem. Soc., **91**, 5783 (1969).

2-3 Reactions of Dialkyl Malonates and Related Compounds

Abstract

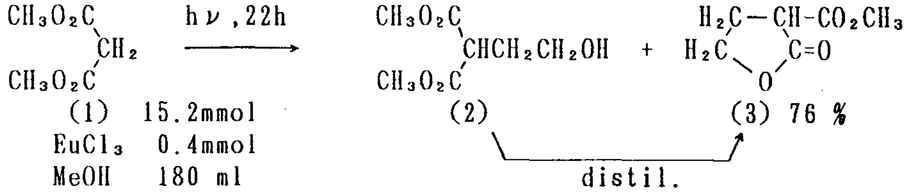
The effective hydroxyalkylation of a malonic acid diester was observed in Eu^{III}/Eu^{II} photoredox system. The photoirradiation of a methanol solution of dimethyl malonate and $EuCl_3$ resulted in the formation of dimethyl hydroxyethylmalonate and its dehydrated product, 2-methoxycarbonyl-γ-butyrolactone. Similar reaction was also observed in the case of diethyl malonate. These reactions were supposed to proceed via the abstraction of α-hydrogen and successive hydroxymethylation. On the other hand, dimethyl maleate and dimethyl fumarate underwent the addition of methanol similar to alkenes and successive lactone formation.

Introduction

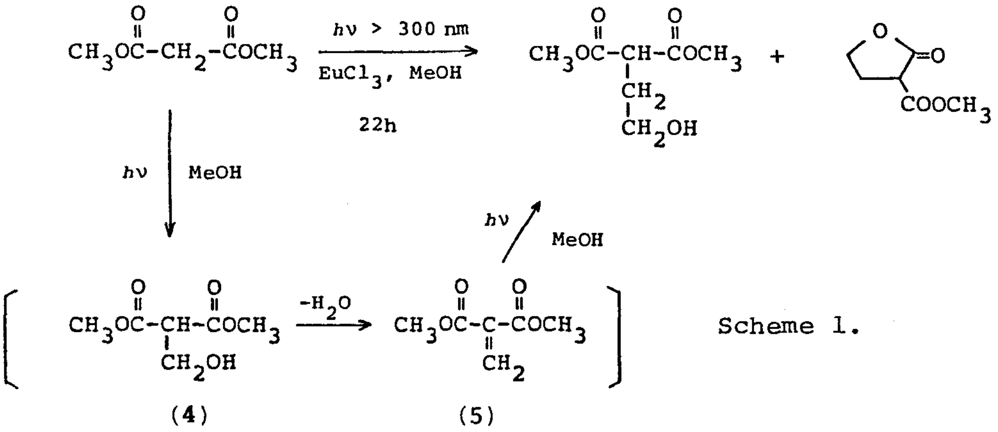
In the previous section, **2-1** and **2-2**, the photoreduction and the hydroxyalkylation of alkenes by use of Eu^{III}/Eu^{II} photoredox system were presented. These reactions were the radical reactions induced by hydrogen atom and hydroxyalkyl radicals produced by the photoredox system and presented appreciable yields. It has been known that the yields and the selectivities of the several radical reactions is improved by the addition of metal ions.1) Therefore, the substrate which can correlate with Eu ion in ground state is also expected to occur the specific reactions. In this section, I tried the reaction of dicarboxylic acid diesters as the substrates by use of a Eu^{III}/Eu^{II} photoredox system.

Results and Discussion

A methanol solution of dimethyl malonate (**1**) and $EuCl_3$ was irradiated (λ>300 nm) for 22 h under Ar. The product was the mixture of dimethyl hydroxyethylmaolnate (**2**) which was confirmed by the NMR spectra and 2-methoxycarbonyl-γ-butyrolactone (**3**). After the distillation, **2** was converted to **3** by dehydration. The isolated yield of **3** was 76 %.

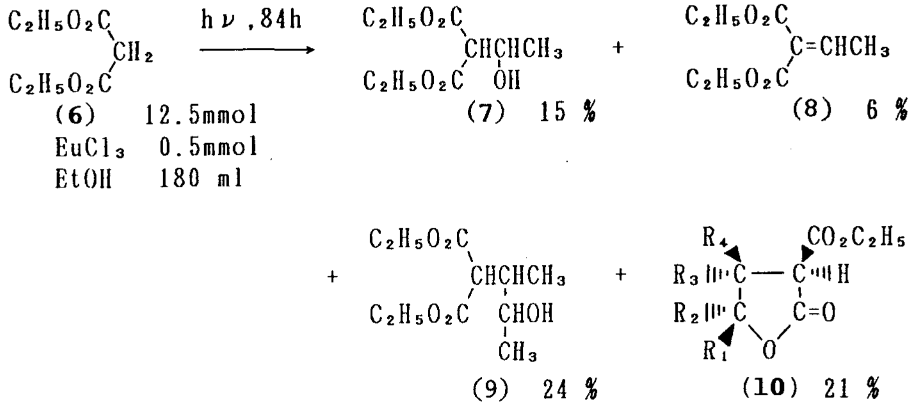


Although the reaction was carried out in methanol, hydroxyethylation took place. The mechanism to explain the fact was suggested as shown in Scheme 1, in which at the initial step of the reaction, the hydroxymethylated product (**4**) was supposed to be produced but it was very unstable and provided its dehydrated alkene product (**5**), and then the further hydroxymethylation occurred to provide **2**.



Scheme 1.

This reaction scheme was confirmed by the reaction of diethyl malonate(**6**) in ethanol. Similar hydroxyalkylation and lactone formation were observed. However, in this case, the hydroxyethylated product (**7**) and the alkene (**8**) were stable and confirmed by the NMR spectra.



(**6**) (**7**) 15 % (**8**) 6 % (**9**) 24 % (**10**) 21 %

	R_1	R_2	R_3	R_4	%
a)	Me	H	Me	H	67
b)	H	Me	H	Me	19
c)	H	Me	Me	H	14

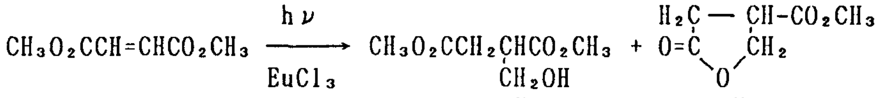
The mechanism of the initial step of the hydroxyalkylation of the malonate was not confirmed yet. This process can be induced by the radical mechanism in which the abstraction of α-hydrogen and successive hydroxyalkylation are supposed and also the one-electron reduction via the electron transfer from the photoexcited Eu^{II} to malonate.$^{2)}$

However, this initial process was confirmed even by a dark reaction of malonate and a corresponding aldehyde (formaldehyde and acetaldehyde), i.e., the Knovenagel-like reaction.[3)]

An ethanol solution of **6** and acetaldehyde provided **7** and **8** in the presence of $EuCl_3$ in dark. Similar phenomenon was observed in the case of **1**-formaldehyde-$EuCl_3$ system, although, the alkene product 5 was unstable and afforded polymeric products. In these reactions, $EuCl_3$ was supposed to act as a Lewis-acid.[3)] The Eu^{III}/Eu^{II} photoredox system provides aldehydes as oxidation products of alcohols and the initial step of present reactions might be induced by the dark reactions (see Chapter 1).

The hydroxyalkylation of the alkene product **5** and **8** was also confirmed by the reaction of dimethyl maleate (**11a**) and dimethyl fumarate (**11b**). A photoirradiation of a methanol solution of **11a** and $EuCl_3$ resulted in the formation of the hydroxymethylated product, dimethyl 2-(hydroxymethyl)succinate (**12a**) and its lactone, 3-methoxycarbonyl-γ-butyrolactone (**13a**) in high yields.[4)] On the other hand, dimethyl fumalate exhibits rather low reactivity.

The contribution of the effects of chelation of the substrte to Eu ion was not confirmed yet, however, the quick transesterifications were observed in the presence of $EuCl_3$ in dark even in room temperature.[5)] This fact suggests the strong interaction of malonate and Eu ion.



cis :a	24 h	74 %	25 %
trans:b	30 h	37 %	27 %
(11)		(12)	(13)

Experimental

Instruments

GLC analyses were carried out on Shimadzu GC-7A gas chromatograph with 2 m glass column packed with OV-17. ^1H and ^{13}C NMR were recorded in $CDCl_3$ solution on Bruker WM-360 using TMS as an internal standard. Mass spectra were run on JEOL JMS-DX300 (GLC, EI, FAB Mass spectrometer) using the same columns as the GLC analysis. Absorption spectra were recorded on Hitachi 323 spectrophotometer. Fluoresence spectra were recorded on Hitachi 850 spectrofluorophotometer.

Photoirradiations were carried out with Pyrex cells (180 mL) connected to gas syringes with Teflon tubings, a high pressure mercury lamp.

Materials

Dimethyl malonate (**1**) and diethyl malonate (**6**) (Nakarai Chemical Co.) were distilled over $MgSO_4$ under reduced argon atmosphere.

Dimethyl maleate (**11a**) (TCI Co.) and dimethyl fumarate (**11b**) (Wako Pure Chemical Co.) were distilled over Na under reduced argon atmosphere.

Alcohols were distilled over CaH_2 prior to use.

$EuCl_3$ was dried under high vacuum prior to use.

TLC plates were DC-Plasticfolien Kiselgel 60 F_{254} (Merck Co.). Silica-gel for chromatography was Kiselgel 60 (Merck Co.). Celite for filtation was Hyflo-Super-Cel (Jhons-Manville Sales Co.)

Procedure

Photoirradiation of **1**

A methanol solution of **1** (2.0 g, 15.2 mmol dm^{-3}) and $EuCl_3$ (150 mg, 0.4 mmol dm^{-3}) was filled in a 180 mL Pyrex cell and irradiated with a high pressure mecury lamp for 22 h under Ar atmosphere. After the irradiation, methanol was removed in vacuo. The mixture was extacted with $CHCl_3$, washed with water two times, dried with $MgSO_4$, and removed $CHCl_3$. The crude product was a colorless oil (1.96 g) and was distilled (bath temp. 80-100 °C/4 mmHg) with a "One-Pot Still" after the NMR analysis. As a sole product **3** was obtained (1.66 g).

Photoirradiation of **6**

A ethanol solution of **6** (2.0 g, 12.5 mmol dm^{-3}) and $EuCl_3$ (180 mg, 0.5 mmol dm^{-3}) was filled in a 180 mL Pyrex cell and irradiated with a high pressure mecury lamp for 84 h under Ar atmosphere. After the irradiation, ethanol was removed in vacuo and the mixture was extracted with Et_2O. The extract was washed with dil. HCl, $NaHCO_3$ solution, and water, and then dried with $MgSO_4$. Ether was removed from the extract in vacuo. The crude products were colorless oil (2.29 g) and separated by a column chromatography on silica-gel (eluent: mixture of Et_2O and n-hexane 2:3) and the three fractions were obtained: **6** and **7**; 0.57 g, **7** and **8**; 0.29 g, **9** and **10**; 0.91 g. The product yields were calculated by the product ratio obtained by ^1H NMR data.

Photoirradiation of **11a**

A methanol solution of **11a** (3.2 g, 22.2 mmol dm^{-3}) and $EuCl_3$ (150 mg, 0.4 mmol dm^{-3}) was filled in a 180 mL Pyrex cell and irradiated with a high pressure mecury lamp for 24 h under Ar atmosphere. After the irradiation, methanol was removed in vacuo, and Et_2O was added. The mixture was filterd through Hyflo super-cel to remove Eu and the colorless oil was obtained by removing ether. TLC ($CHCl_3$) showed two spots (Rf=0.16 and 0.45). The crude product was separated by column chromatography on silica-gel (eluent: $CHCl_3$) and the three fractions were obtained: 12a [Rf=0.16]; 1.0 g, **12a** and **13a** ; 0.36 g, **13a** [Rf=0.35]; 2.35 g. The yields were calculated on the basis of the ratio of **12a** and **13a** obtained from ^1H NMR data.

Photoirradiation of **11b**

A methanol solution of **11b** (3.2 g, 22.2 mmol dm^{-3}) and $EuCl_3$ (150 mg, 0.4 mmol dm^{-3}) was filled in a 180 mL Pyrex cell and irradiated with a high pressure mercury lamp for 30 h under Ar atmosphere. After the irradiation the reaction mixture was worked up by the same procedure in the case of **11a**. The three fractions were obtained: **11b** and **13b**; 1.07 g, **13b**; 1.00 g, **12b**; 1.44 g. The yields were calculated on the basis of the ratio of **12b** and **13b** obtained from ^1H NMR data.

Identification of Products

Dimethyl hydroxyethylmalonate(**2**): not isolated, but identified as a mixture with (**3**) by ^{1}H and ^{13}C NMR signal; ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=3.75 (s, 3H), 3.68 (t, J=6.1 Hz, 1H), 3.17 (bs, 1H), 2.15 [d (J=6.1 Hz) and t (J=6.6 Hz), 2H], 2H of [$-C\underline{H}_2-OH$] was not identified, because its signal was in multiplet of 4.52-4.32; ^{13}C NMR ($CDCl_3$, $SiMe_4$) δ=174.3, 63.4, 52.8, 48.1, 29.5.

2-Methoxycarbonyl-γ-butyrolactone (**3**); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=4.48 (ddd, J=5.3 , 8.2, and 8.9 Hz, 1H), 4.35 (ddd, J=7.4, 7.5, and 8.9 Hz, 1H), 3.81 (s, 3H), 3.59 (dd, J=7.9 and 8.9 Hz, 1H), 2.68 (dddd, J=7.4, 7.9, 8.2 and 13.1 Hz, 1H), 2.54 (dddd, J=5.3, 7.5, 9.3, and 13.1 Hz, 1H); ^{13}C NMR($CDCl_3$, $SiMe_4$, off-resonance) δ=172.3 (s), 168.3 (s), 67.4 (t), 53.0 (q), 45.8 (d), 26.5 (t); m/z (relative intensity) 145 (M^++1, 2%), 144 (4, M^+), 113 (29), 100 (32), 69 (100), 59 (22), 55 (39), 41 (51); Anal. Calcd for $C_6H_8O_4$: C, 50.00; H, 5.60. Found: C, 49.74; H, 5.62.

1,1-bis(Ethoxycarbonyl)-2-hydroxypropane (**7**) : not isolated, but identified as a mixture with (**8**) by ^{1}H and ^{13}C NMR signal; ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=4.21 (q, J=7.06 Hz, 2H), 4.19 (q, J=7.06 Hz, 2H), 3.62 [d (J=9.1 Hz) and q (J=7.0 Hz), 1H], 3.46 (d, J=9.2 Hz, 1H), 1.28 (t, J=7.0 Hz, 3H), 1.27 (t, J=7.0 Hz, 3H), 1.25 (d, J=7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, $SiMe_4$) δ=167.7 (s), 167.3 (s), 73.9 (d), 61.4 (t), 59.0 (d), 18.0 (q), 14.1 (q); m/z (relative intensity) 204 (M^+, 14%), 203 (100).

1,1-bis(Ethoxycarbonyl)-1-butene **(8)**: ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=7.09 (q, J=7.1 Hz, 2H), 1.96 (d, J=7.2 Hz, 3H), 1.34 (t, J=7.1 Hz, 3H), 1.29 (t, J=7.1 Hz, 3H); ^{13}C NMR ($CDCl_3$, $SiMe_4$) δ=165.4 (s), 163.4 (s), 144.6 (d), 130.1 (s), 61.2 (t), 15.4 (q), 14.2 (q); m/z (relative intensity) 186 (M^+, 10%), 141 (100).

Dimethyl 2-(hydroxymethyl)succinate **(12a**, derived from dimethyl maleate); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=3.82 (d, J=5.4 Hz, 2H), 3.73 (s, 3H), 3.70 (s, 3H), 3.04 (dist. quintet, 1H), 2.87 (bs, 1H), 2.78 (dd, J=7.5 Hz and 16.8 Hz, 1H), 2.63 (dd, J=6.2 and 16.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, $SiMe_4$) δ=173.9 (s), 172.7 (s), 62.6 (t), 52.0 (q), 50.3 (q), 44.1 (q), 32.7 (t); Anal. Calcd for $C_7H_{12}O_5$: C, 47.72; H, 6.87. Found: C, 47.77, H, 6.86.

Dimethyl 2-(hydroxymethyl)succinate **(12b**, derived from dimethyl fumalate); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=3.83 (dist. t, J=5.4 Hz,2H), 3.73 (s, 3H), 3.70 (s, 3H), 3.04 (dist. quintet, 1H), 2.87 (bt, J=6.0 Hz, 1H), 2.79 (dd, J=7.5 and 16.8 Hz, 1H), 2.64 (dd, J=6.3 and 16.8 Hz, 1H); m/z (relative intensity) 176 (M^+, 1%), 145 (37), 127 (38), 114 (74), 103 (100), 55 (78).

3-Methoxycarbonyl-γ-butyrolactone **(13a**, derived from dimethyl maleate); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=4.52 (dd, J=8.4 and 9.3 Hz, 1H), 4.46 (dd, J=6.6 and 9.4 Hz, 1H), 3.78 (s, 3H), 3.48 (dist. quintet, 1H), 2.88 (dd, J=7.3 and 18.0 Hz, 1H), 2.76 (dd, J=9.6 and 17.9 Hz, 1H); ^{13}C NMR ($CDCl_3$, $SiMe_4$) δ=175.3 (s), 171.9 (s), 69.2 (t), 52.7 (q), 39.9 (d); m/z (relative intensity) 145

(M^++1, 4%), 144 (1, M^+), 116 (24), 102 (37), 59 (31), 55 (100); Anal. Cacld for $C_6H_8O_4$: C, 50.00; H, 5.60. Found : C, 49.74 ; H, 5.46.

3-Methoxycarbonyl-γ-butyrolactone (**13b**, derived from dimethyl fumalate); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=4.53 (dd, J=8.4 and 9.4 Hz, 1H), 4.45 (dd, J=6.4 and 9.3 Hz, 1H), 3.77 (s, 3H), 3.49 (dist. quintet, 1H), 2.87 (dd, J=7.3 and 17.9 Hz, 1H), 2.76 (dd, J=9.7 and 17.9 Hz, 1H).

Photoisomerization of dimethyl fumalate(**11b**): **11a**; not isolated but identified as a mixture of **1b** by ^{1}H NMR signal. ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=6.28 (s, 2H), 3.79 (s, 6H). The proton ratio was not derived from the integral values but the intensities.

Reference and Note

1. F. Minisci, Acc. Chem. Res., **8**, 125 (1975).
2. The fluorescence of the photoexcited Eu^{II} was quenched effectively by malonate in the presence of 18-crown-6 ether. The quenching rate constant was over than 10^9 $mol^{-1}dm^3s^{-1}$.
3. W. Lehnert, Tetrahedron Lett., **1970**, 4723.
4. Similar reactions were also observed by the photoirradiation with $TiCl_4$ [T. Sato et al., Bull. Chem. Soc. Jpn., **50**, 2714 (1977)] and also by the γ-irradiation [M. Tokuda, V. V. Chung, A. Suzuku, and M. Itoh, Chem. Lett., **1972**, 405].
5. In the cases of dimethyl malonate-EtOH and diethyl malonate-MeOH system, the transesterifications were observed even at room temperature. In the case of dimethyl malonate-n-BuOH system, the reaction was induced by a refluxing.

2-4 Reactions of 1,3-Dimethyluracil and Its Derivatives

Abstract

Irradiation of a methanol solution of $EuCl_3$ and 1,3-dimethyluracil through a Pyrex filter induced a regioselective hydroxymethylation at C-6 position in high efficiency via an electron-transfer mechanism. Similar addition of solvent was observed in ethanol, 2-propanol, and tetrahydrofuran solution.

Introduction

The photoexcited Eu^{II} is a very strong reductant of which the redox potential is -2.4V[1)] and it is capable of inducing one-electron reduction of the substrate added to the reaction system.

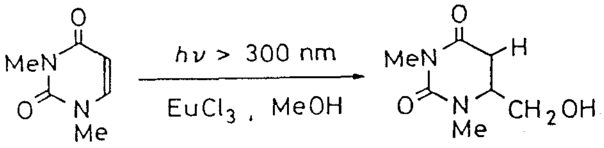
The reactivity of radical anions of uracil and its derivatives have been investigated widely in connection with a radiation damage of nucleic acid.[2)] However, it have been not well defined for example, dehalogenation of halouracils,[3)] the position of protonation[4)] etc. On the other hand, the photochemical reactivity of uracil and its derivatives towards alcohol is a subject of significant interest to the investigators studying the photoinduced cross-linking of uracil and amino acid.[5,6)] Little, however, is known about the photoredox reaction of these compounds i.e., the reaction via radical anions of these compounds. Furthermore, the present reaction also provides a convenient and useful method for the introduction of a hydroxymethyl group into the 6 position of the pyrimidine and potential use for the analogous synthesis of biological importance.

In the present study, it was found that when 1,3-dimethyluracil and its derivatives are used as a substrate, a regioselective hydroxymethylation takes place in high efficiency probably via an electron transfer mechanism.

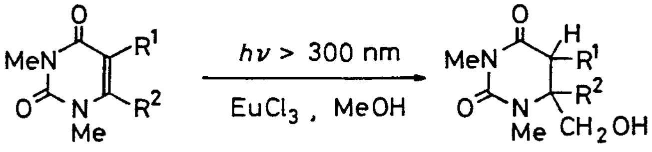
Results and Discussion

A methanol solution of $EuCl_3$ (5 mmol dm^{-3}) and 1,3-dimethyluracil (**1**a, 0.1 mol dm^{-3}) was irradiated with a high pressure mercury lamp through a Pyrex filter under argon. The product was isolated by column chromatography on silica-gel using benzene:acetone (4:1, v/v) and identified as 1,3-dimethyl-6-hydroxymethyl-5,6-dihydrouracil (**2**a) on the basis of its spectral data. The results of the photolysis of 1,3-dimethyluracil and its derivatives (**1**a-e) are shown in Table 1.

The photoirradiation in ethanol, 2-propanol, and tetrahydrofuran also resulted in the formation of respective solvent adducts (**3**a, **4**a, and **5**a) in high yields.



(1a) 100 mmol·dm^{-3} (2a) 98 %



(1) (2)

Table 1. Photolysis of **1** in methanol.[a)]

1	R^1	R^2	[1] mmol dm^{-3}	Irrad. time/h	Conv. /%	Yield of **2**/%[b)]
1a	H	H	20	3	100	84
			100	6	89	98
			200	8	66	95
1b	CH_3	H	100	5	88	91[c)]
1c	F	H	100	5	64	78[d)]
1d	Cl	H	50	5	71	57[e)]
				12	100	32 (35)[f)]
1e	H	CH_3	100	5	8	40[g)]

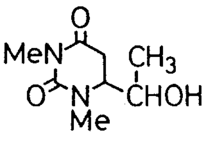
a) $[EuCl_3]$=10 mmol dm^{-3}, Ar saturated methanol solution, Pyrex filter.

b) Yields are based on the amount of **1** consumed.

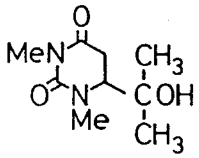
c) cis; 57%, trans; 24% d) cis; 16%, trans; 62%

e) cis; 44%, trans; 13%

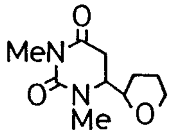
f) Yield of **2a**; a dechlorinated product of **2d** found on prolonged irradiation.



(**3a**)



(**4a**)



(**5a**)

Characteristic features of this reaction are summarized as follows: (i) In all derivatives (**1a**-**e**), a regioselective hydroxymethylation occurs at the 6 position. (ii) The yields of **2a** and **2b** are very high, although the yields of halogenated derivatives (**2c** and **2d**) are rather low. In the case of **1d**, further dechlorination of **2d** and successive formation of **2a** was observed which became a main path at a prolonged irradiation (see Fig. 1). (iii) The reaction does not proceed in the absence of $EuCl_3$. The wavelength region of the effective light for this reaction is 300-350 nm. The absorption of the incident light occurs mainly in Eu^{III} ion and also in Eu^{II} ion once formed. (iv) A catalytic amount of $EuCl_3$ is enough for inducing this reaction and the yield of **2a** based on $EuCl_3$ used goes up to over 1250%. (v) The yield of **2b** is very high as well as that of **2a**, although the 6-methyl derivative (**1e**) shows an extremely low reactivity and 92% of **1e** was recovered after 5 h irradiation.

In order to get insight of this reaction, deuterium labeled experiments were carried out. When a methanol-d solution (CH_3OD) of **1a** (0.1 mol dm^{-3}) and $EuCl_3$ (0.01 mol dm^{-3}) was irradiated to about 50% conversion, the incorporation of a deuterium atom in **2a** was observed by the mass spectra (d_1: 99%) and the deuterium was found preferentially at the 5 position of **2a** by NMR spectra (100%). On the other hand, the deuterium incorporation in the recovered **1a** was negligibly small (less than 3%). These facts suggest that an alcoholic proton selectively adds to the 5 position, preferably via the radical anion of **1a** (see Scheme 1) because such a high regioselectivity cannot be

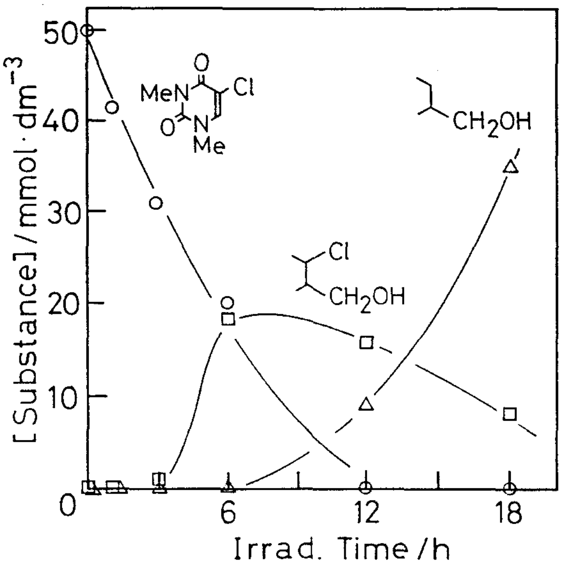
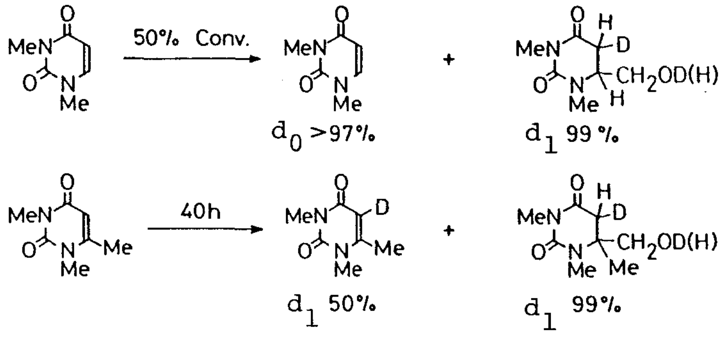


Fig. 1. Reaction of **1d** as a function of irradiation time ; [**1d**]=50 mmol dm^{-3}, [EuCl$_3$]=10 mmol dm^{-3}, 2 mL methanol solution, Ar saturated, Pyrex filter.

Deuterium Incorporation in CH_3OD



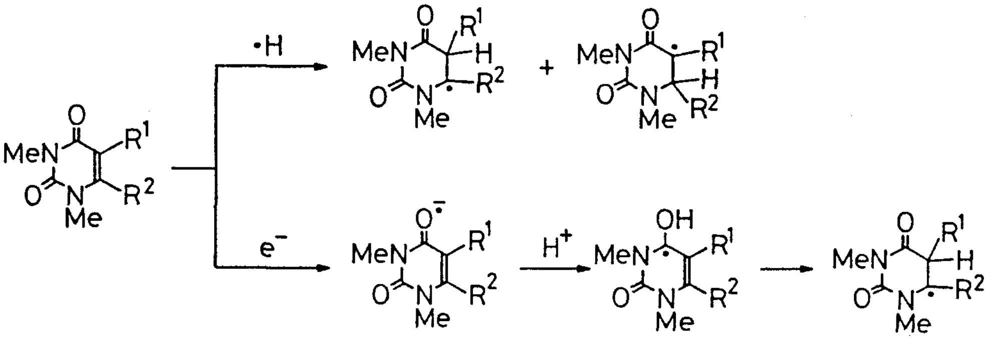
reasonably explained by a free radical addition to the C-C double bond of uracil derivatives.$^{7)}$ When **1e** was irradiated in methanol-d in the presence of $EuCl_3$ for 40 h, about 50% incorporation of deuterium in the 5 position of the recovered **1e** was observed. No deuterium incorporation in **1e** was detected after 24 h in the dark. The photoproduct(**2e**) also contained a deuterium at C-5 position. Similar deuterium incorporations were observed in ethanol-d solutions. Therefore, the very low reactivity of **1e** can be explained as that a hydrogen added radical of **1e** (**6c**) hardly recombines with a hydroxymethyl radical to give **2e** due to the steric hindrance of the 6-methyl group. The radical (**6**) mainly undergoes deprotonation to give **1e** which causes the deuterium incorporation.

On the basis of these observations, a reasonable mechanism for the formation of 2 is shown in Scheme 2.

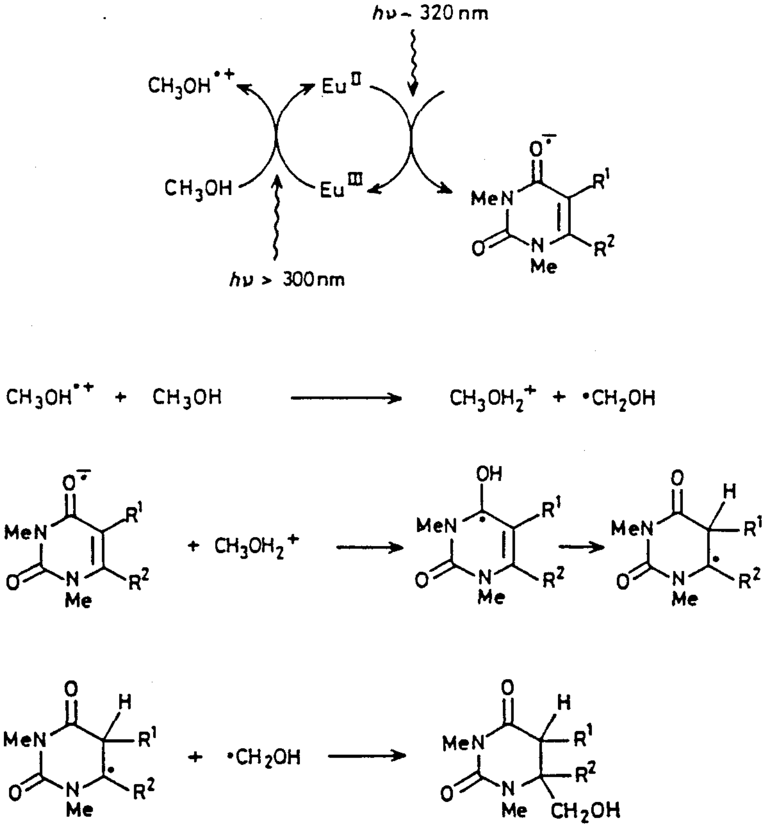
The formation of Eu^{II} which is the key active species for the reduction of **1** was confirmed by the absorption spectra (λ_{max} 330 nm)$^{8)}$ and also fluorescence spectra (λ_{max} 489 nm)$^{9)}$ of the methanol solution of $EuCl_3$ after the irradiation. The fluorescence, which was extremely enhanced by the addition of 18-crown-6 ether as reported by Adachi et al.,$^{9)}$ was found to be quenched by **1**$^{10)}$.

Dechlorination of **2d** induced by a prolonged irradiation may also proceed via the electron transfer mechanism (Scheme 3). Similar dehalogenation induced by one-electron reduction has been reported in 5-bromouracil$^{11)}$ and 5-bromo-6-hydroxythymine.$^{12)}$

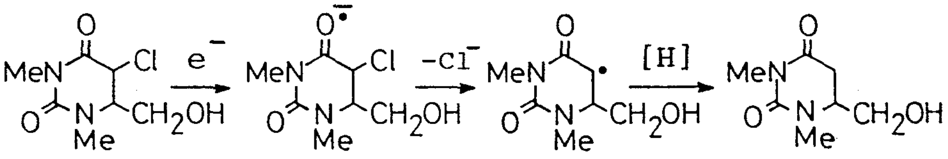
Selective Formation of the Radical



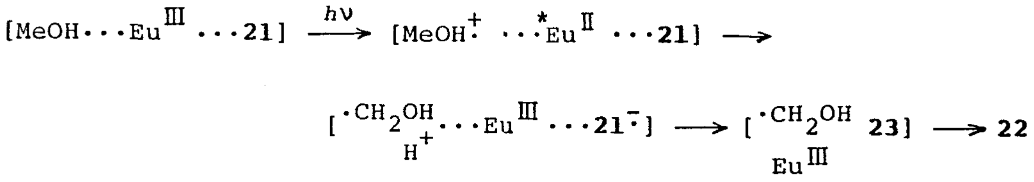
Scheme 1.



Scheme 2.



Scheme 3.



$$[\mathrm{MeOH}\cdots\mathrm{Eu}^{\mathrm{III}}\cdots\mathbf{21}] \xrightarrow{h\nu} [\mathrm{MeOH}^{\dot{+}}\cdots{}^{*}\mathrm{Eu}^{\mathrm{II}}\cdots\mathbf{21}] \longrightarrow$$

$$[\cdot\mathrm{CH_2}\underset{\mathrm{H}^{+}}{\mathrm{OH}}\cdots\mathrm{Eu}^{\mathrm{III}}\cdots\mathbf{21}^{\dot{-}}] \longrightarrow [\underset{\mathrm{Eu}^{\mathrm{III}}}{\cdot\mathrm{CH_2OH}}\ \mathbf{23}] \longrightarrow \mathbf{22}$$

Scheme 4.

In these reactions, no dimer products were observed and the yields and the selectivity were so high despite the possible radical coupling reactions. The facts suggest the interaction of Eu ion and uracil. In fact, the complex formation of uracil and lanthanide ions was reported$^{13)}$ and the absorption spectra suggested the CT interaction and the coexistance of Eu ion prevented the GLC analysis of uracils for peak broadness and reducing sensitivities which was repaired by adding EDTA-2Na as a cheleting agent. Furthermore, it was reported that the CT-excitation of $\mathrm{Eu^{II}}$-$\mathrm{H_2O}$ provided the excited $\mathrm{Eu^{II}}$.$^{8)}$

Scheme 5 shows the possible one-photon mechanism in the present reactions. Sato et al. have proposed a long-range electron transfer mechanism in the photoreaction of $\mathrm{TiCl_3}$ which is a similar type of reaction to the present system.$^{14)}$

Experimental

Instruments

Photoirradiation was carried out with a Pyrex cell (5 mL or 180 mL) and a 350 W high pressure mercury lamp. For quantitative analysis, a merry-go-round appararus was used. Sonications were carried out with a BRANSONIC B-32H ultrasonic cleaner. GLC analyses were carried out on a Shimadzu GC-7A gas chromatograph with 1 m or 2 m glass column packed with OV-17. ^1H and ^{13}C NMR spectra were measured in $CDCl_3$ solution with a Bruker WM-360 using TMS (tetramethylsilane) as an internal standard. The mass spectra were recorded on a JEOL JMS-DX300 with a JMA-3100 data processor (In this system GC, FAB, EI high resolution, and EI low resolution mode are selectable.). Absorption spectra and fluorescence spectra were recorded on a Hitachi 323 spectrophotometer and a Hitachi 850 spectrofluorophotometer, respectively.

Materials

$EuCl_3$ $6H_2O$ was obtained from Nakarai Co. and used without further purifications.

1,3-Dimethyluracil, 1,3-dimethylthymine, 1,3-diemthyl-5-fluorouracil, and 1,3-dimethyl-5-chlorouracil were synthesized from the corresponding bases obtained from Sigma Co. by use of dimethyl sulfate.

EDTA-2Na was obtained from Nakarai Co.

CH_3OD was obtained from Merck Co and used without further purifications. All solvents except for CH_3OD were distilled over

CaH_2 prior to use.

Silica-gel for column chromatograpy was Kieselgel 60 (Merck Co.).

Procedure

A solution of uracil and $EuCl_3$ was filled in a Pyrex cell and degassed by sonication for 5 minutes and saturated with Ar by bubbling for 10 minutes and then irradiated with a high pressure mercury lamp at running water temperature. For quantitative analysis, EDTA-2Na was added to the irradiated reaction mixture to remove Eu by chelation, and GLC anaysis was carried out. For preparative run, the solvent was removed in vacuo and the products were extracted by dichloromethane and isolated by column chromatograpy on silica-gel using benzene-acetone mixture as an elution solvent.

Identification of the Products

2a, **3a**, **4a**, and **5a** were synthesized previously (Ref. 4).

2a: Viscous oil; Found: M^+, 172.08604. $C_7H_{12}N_2O_3$ requires m/z, 172.08471; m/z 172 (M^+, 2%), 141 (81), 84 (81), 56 (6), 42 (100), and 28 (14); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=27.04 (q, N-$\underline{C}H_3$), 33.25 (t, C-$\underline{C}H_2$), 35.25 (q, N-$\underline{C}H_3$), 55.14 (d, N-$\underline{C}$H-), 66.06 (t, $\underline{C}H_2OH$), 153.0 (s, $\underline{C}$=O), and 169.48 (s, $\underline{C}$=O); ^1H NMR ($CDCl_3$, $SiMe_4$) δ=2.84 (m, 2H), 3.06 (s, 3H), 3.09 (s, 3H), 3.50 (m, 1H), 3.68 (m, 2H), and 4.28 (br s, 1H, this peak disappeared on shaking with D_2O).

3a; adhesive crystals; Found: M^+, 186.09885. $C_8H_{14}N_2O_3$ requires m/z, 186.10035; m/z 186 (M^+, 1%), 149 (1), 141 (94), 127 (2), 125 (1), 113 (4), 99 (1), 84 (100), 70 (2), 55 (7), 45 (5), 42 (81); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) $\delta=20.04$ (q, $\underline{C}H_3$-C-OH), 27.38 (q, N-$\underline{C}H_3$), 31.12 (t, $\underline{C}H_2$), 35.98 (q, N-$\underline{C}H_3$), 59.54 (d, N-$\underline{C}$H-), 67.35 (C-$\underline{C}$-OH), 153.85 (s, $\underline{C}$=O), 169.50 (s, $\underline{C}$=O); ^1H NMR ($CDCl_3$, $SiMe_4$) $\delta=1.22$ (d, J=6.43 Hz, 3H), 2.79 (d, J=7.2 Hz, 1H), 2.84 (d, J=2.1 Hz, 1H), 3.04 (brs, 1H), 3.09 (s, 3H), 3.12 (s, 3H), 3.20 (dt, J=5.9 and 1.8 Hz, 1H), 4.03 (dq, J=6.5 and 4.0 Hz, 1H).

3a-2; ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) $\delta=19.77$ (q, $\underline{C}H_3$-C-OH), 27.35 (q, N-$\underline{C}H_3$), 32.95 (t, $\underline{C}H_2$), 37.59 (q, N-$\underline{C}H_3$), 59.41 (d, N-$\underline{C}$H-), 68.96 (d, C-$\underline{C}$-OH), 153.51 (s, $\underline{C}$=O), 169.34 (s, $\underline{C}$=O); ^1H NMR ($CDCl_3$, $SiMe_4$) $\delta=1.20$ (d, J=6.61 Hz, 3H), 2.74 (d, J=7.17 Hz, 1H), 2.83 (d, J=4.8 Hz, 1H), 3.04 (brs, 1H), 3.13 (s, 3H), 3.15 (s, 3H), 3.30 (ddd, J=7.2, 7.6, and 4.7 Hz, 1H), 3.94 (dq, J=6.3 and 6.2 Hz, 1H).

4a; viscous oil; Found: M^+, 200.11417. $C_9H_{16}N_2O_3$ requires m/z, 200.11599; m/z 200 (M^+, 1%), 185 (2), 149 (1), 141 (100), 138 (10), 135 (7), 113 (17), 99 (2), 84 (37), 71 (3), 70 (3), 59(24), 42 (58); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) $\delta=26.76$ (q, $\underline{C}H_3$-C-OH), 27.11 (q, $\underline{C}H_3$-C-OH), 27.25 (q, N-$\underline{C}H_3$), 32.47 (t, $\underline{C}H_2$), 39.20 (q, N-$\underline{C}H_3$), 62.77 (d, N-$\underline{C}$H-), 74.73 ($\underline{C}$-OH), 153.63 (s, $\underline{C}$=O), 169.63 (s, $\underline{C}$=O); ^1H NMR ($CDCl_3$, $SiMe_4$) $\delta=1.23$ (s, 3H), 1.26 (s, 3H), 2.82 (d, J=2.66 Hz, 1H), 2.83 (d, J=3.12, 1H), 3.13 (s, 3H), 3.17 (s, 3H), 3.24 (dd, J=3.30 and 3.29 Hz, 1H).

5a; viscous oil; ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=25.62 (t, C-3 or C-4 of THF), 28.25 (t, C-4 or C-3 of THF), 28.39 (q, N-$\underline{C}H_3$), 32.16 (t, C-$\underline{C}H_2$), 35.98 (q, N-$\underline{C}H_3$), 57.11 (d, N-$\underline{C}$H), 68.37 (t, C-5 of THF), 79.10 (d, C-2 of THF), 153.67 (s, $\underline{C}$=O), 168.90 (s, $\underline{C}$=O); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=1.86-2.00 (m, 4H), 2.74-2.93 (m, 2H), 3.11 (s, 3H), 3.15 (s, 3H), 3.35-3.42 (m, 1H), 3.70-3.88 (m, 3H).

2b-cis; viscous oil; Found: M^+, 186.10047. $C_8H_{14}N_2O_3$ requires m/z, 186.10035; m/z 186 (M^+, 1%), 155 (100), 98 (100), 70 (81) 57 (76), 42 (97), 31 (63), and 28 (65); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=16.96 (q, C-$\underline{C}H_3$), 27.45 (q, N-$\underline{C}H_3$), 35.88 (q, N-$\underline{C}H_3$), 37.88 (d, C-$\underline{C}$H-), 61.94 (t, $\underline{C}H_2$OH), 62.13 (d, N-$\underline{C}$H-), 153.11 (s, $\underline{C}$=O), and 173.38 (s, $\underline{C}$=O); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=1.33 (d, J=7.3 Hz, 3H), 2.83 (q, J=7.3 Hz, 1H), 3.10 (s, 3H), 3.11 (s, 3H), 3.15 (dt, J=0.8 and 4.7 Hz, 1H), 3.66 (d, J=4.7 Hz, 2H), and 4.10 (br s, 1H, this peak disappeared on shaking with D_2O).

2b-trans; viscous oil; Found: M^+, 186.10061. $C_8H_{14}N_2O_3$ requires m/z, 186.10035; m/z 186 (M^+, 2%), 155 (100), 98 (95), 70 (62), 57 (63), 42 (98), 31 (36), 28 (27) ; ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=11.11(q, C-$\underline{C}H_3$), 27.44 (q, N-$\underline{C}H_3$), 35.20 (q, N-$\underline{C}H_3$), 36.79 (d, N-$\underline{C}$H-), 58.61 (t, $\underline{C}H_2$-OH), 60.56

(d, N-$\underline{C}$H-), 154.32 (s, $\underline{C}$=O), 172.57 (s, $\underline{C}$=O); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=1.26 (d, J=7.1 Hz, 3H), 2.99 (q, J=6.9 Hz, 1H), 3.07 (s, 3H), 3.08 (s, 3H), 3.40 (t, J=3.2 Hz, 1H), 3.69 (d, J=3.3 Hz, 2H), 4.38 (brs, 1H).

2c-cis; viscous oil; Found: M^+, 190.07506. $C_7H_{11}N_2O_3F$ requires m/z, 190.07529; m/z 190 (M^+, 7%), 159 (64), 140 (9), 102 (98), 74 (100), 58 (23), 56 (23), 42 (65), 28 (54); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=27.68 (q, N-$\underline{C}H_3$), 34.54 (q, N-$\underline{C}H_3$), 58.88 and 58.99 (t, C-$\underline{C}H_2$OH), 60.47 (d, N-$\underline{C}$H-C), 84.37 and 86.34 (d, -$\underline{C}$FH), 152.53 (s, $\underline{C}$=O), 164.87 (s, $\underline{C}$=O); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ3.10 (s, 3H), 3.15 (s, 3H), 3.35 (d, J=40.51 Hz, 1H), 3.70 (ddt, J=18.00 and 3.20 Hz, 1H), 3.82 (d, J=5.11 Hz, 2H), 4.09 (brs, 1H).

2c-trans; colorless needle, mp 138°C; Found: M^+, 190.07348. $C_7H_{11}N_2O_3F$ requires m/z, 190.07529; m/z 190 (M^+, 5%), 159 (41), 140 (8), 102 (75), 74 (100), 58 (18), 42 (44), 31 (26); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ =27.56 (q, N-$\underline{C}H_3$), 35.29 (q, N-$\underline{C}H_3$), 57.34 (t, C-$\underline{C}H_2$OH), 58.63 (d, N-$\underline{C}$H-), 80.83 and 82.92 (d, $\underline{C}$HF), 153.20 (s, N-$\underline{C}H_3$), 164.64 (s, N-$\underline{C}H_3$); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=2.37 (brs, 1H), 3.12 (s, 3H), 3.15 (dd, J=35.2 and 1.5 Hz, 1H), 3.16 (s, 3H), 3.73 (dt, J=5.0 and 1.8 Hz, 1H), 3.92 (d, J=2.77 Hz, 2H).

2d-cis; viscous oil; Found: M^+, 206.03957. $C_7H_{11}N_2O_3Cl$ requires m/z, 206.04574; m/z 206 (M^+, 5%), 177 (30), 175 (89), 141 (20), 140 (35), 120 (34), 118 (100), 90 (41), 83 (33), 55 (42), 42

(73), 27 (89); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=27.99 (q, N-$\underline{C}H_3$), 35.72 (q, N-$\underline{C}H_3$), 52.15 (d, N-$\underline{C}$H-C), 60.59 (t, C-$\underline{C}H_2$OH), 63.12 (d, $\underline{C}$HCl), 152.21 (s, $\underline{C}$=O), 165.84 (s, $\underline{C}$=O); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=3.13 (s, 3H), 3.15 (s, 3H), 3.60 (dt, J=1.5 and 5.0 Hz, 1H), 3.77 (d, J=4.47 Hz, 2H), 4.00 (brs, 1H), 4.62 (d, J=1.63 Hz, 1H).

2d-trans; colorless adhesive crystal; Found: M^+, 206.03921. $C_7H_{11}N_2O_3Cl$ requires m/z, 206.04574; m/z 206 (M^+, 2%), 177 (18), 175 (54), 141 (10), 140 (18), 120 (19), 118 (59), 90 (28), 83 (20), 55 (28), 42 (100), 31 (20); ^{13}C NMR ($CDCl_3$, $SiMe_4$, off-resonance) δ=28.52 (q, N-$\underline{C}H_3$), 35.15 (q, N-$\underline{C}H_3$), 53.92 (d, N-$\underline{C}$H-), 57.95 (t, C-$\underline{C}H_2$OH), 60.43 (d, $\underline{C}$HCl), 153.05 (s, $\underline{C}$=O), 166.08 (s, $\underline{C}$=O); ^{1}H NMR ($CDCl_3$, $SiMe_4$) δ=2.2 (brs, 1H), 3.14 (s, 3H), 3.19 (s, 3H), 3.66 (dt, J=6.3 and 3.2 Hz, 1H), 3.83 (d, J=4.4 Hz, 2H), 4.85 (d, J=6.3 Hz, 1H).

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10. Methanol solutions of $EuCl_3$ (10 mmol dm^{-3}) and **1** (5-100 mmol dm^{-3}) were preirradiated in the presence of 18-crown-6 ether (100 mmol dm^{-3}) in order to get a photostationary concentration of Eu(II) and the fluorescence lifetime at 446 nm were measured by the laser flash photolysis (308 nm,

15 ns, 100 mJ). The quenching rate constants were obtained from the plots of the reciprocal of the fluorescence lifetime vs. the concentration of **1** ($k_{1\mathbf{a}}=7.4\times10^8$, $k_{1\mathbf{b}}=3.2\times10^8$, $k_{1\mathbf{c}}=1.6\times10^9$, $k_{1\mathbf{d}}=2.0\times10^9$, $k_{1\mathbf{e}}=3.2\times10^8$ $dm^3mol^{-1}s^{-1}$). The details are shown in Chapter 4.

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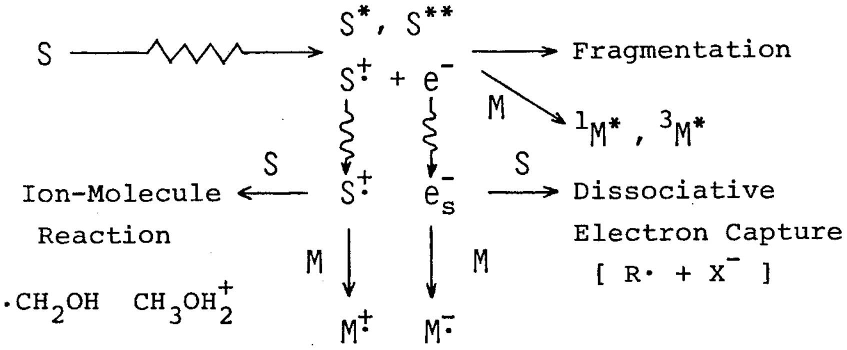
Chapter 3 One-Electron Reduction of Uracil and Its Derivatives Induced by Ionizing Radiation

Introduction

In Chapters 1 and 2, the primary character and the application of the photoredox system of Eu^{III}/Eu^{II} was presented. Especially, the reaction of 1,3-dimethyluracil and its derivatives was the regioselective hydroxymethylation via a one-electron reduction mechanism (see 2-4). In this chapter, the one-electron reduction of uracil and its derivatives induced by the irradiation of ionizing radiation was presented.

Irradiation with ionizing radiation is one of the most powerful and unique methods of initiating chemical reactions since the energy of radiation is high enough to excite and ionize molecules and the energy deposition processes are well established. The primary active species resulting from irradiation are electrons, radical ions, excited molecules, active atoms, and free radicals, which are all synthetically useful. Their contributions to chemical synthesis are strongly influenced by the irradiation conditions. In solutions, active species of solute are mainly produced by the secondary attack of the active species primarily formed from the solvent molecules. A striking characteristic of ionizing radiation is that for a variety of substrate these active species are produced nonselectively. Furthermore, by choice of solvents and reaction conditions, one can often make the fraction of any one of these active species at least 90 % of the total. By use of polar solvent such as methanol, tetrahydrofuran, and etc., it has been well known that the irradiation of ionizing radiation results in the formation of the radical cations of the solvent and solvated electrons and in the presence of the substrate, these primary species are transformed into the radicals of solvent and the radical anion of the substrate by the attachment of the solvated electrons when the electron affinity of the substrate is large. The initiall processes of radiation-induced reactions are summarized in Scheme 1.



Scheme 1.

In the section 1 of this chapter, it was presented that the reaction of 1,3-dimethyluracil and its derivatives induced by γ-irradiation and in the section 2, it was presented that the pulse radiolysis study of the one-electron reduction of uracil and its derivatives.

3-1 One Electron Reduction of 1,3-Dimethyluracil and Its Derivatives Induced by γ-Irradiation

Abstract

γ-Radiolysis of 1,3-dimethyluracil and its derivatives in methanol results in the regioselective hydroxymethylation at C-5 position of the pyrimidine ring. Analogous additions of ethanol, 2-propanol and tetrahydrofuran to 1,3-dimethyluracil occur in high efficieny. A mechanism via the one-electron reduction of 1,3-dimethyluracil is presented and compared with that of the photochemical reactions.

Introduction

The radiation chemistry of nucleobases, as well as the photochemical reactions, has been investigated in connection with the damage of nucleic acids.1) As the typical reactions of uracil and its drivatives, dimerization, addition of some molecules such as amino acids, alcohols and water, and dihydrouracil formation have been reported. In particular, the bimolecular reactions with alcohols are of biological importance in connection with crosslinkng of nucleic acids to sugars and amino acids with an alcoholic side chain.2) However, many investigations previously carried out were focused on the reactions in aqueous solutions, where the mechanistic details are rather complicated by many side reactions and not yet clarified.

On the other hand, it has been well-known that the primary process for the γ-radiolysis of polar liquid such as methanol is an ionization producing radical cations of solvent molecules and solvated electrons. In the case of a methanol solution, these primary species are transformed into hydroxymethyl radicals and the radical anions of the solute by the attachment of solvated electrons when the electron affinity of the solute is large. Therefore, γ-radiolysis of a methanol solution of uracil derivatives provides a reaction system which is quite similar to that of the photoredox system of Eu^{III}/Eu^{II} and might become an alternative and simple method for the regioselective hydroxymethylation which was achieved by the photchemical reactions.

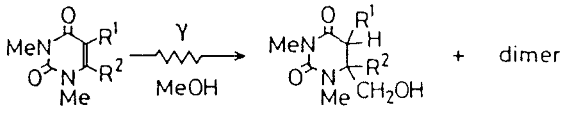
In this section, I present the γ-radiolysis of 1,3-dimethyluracil and its derivatives in alcohols and compare the mechanistic features of these reactions with those of the photochemical reactions.

Results and Discussion

γ-Radiolysis of 1,3-dimethyluracil(1a) in methanol was carried out in a Pyrex cell using a ^{60}Co source at a dose of 0.1 MGy at room temperature under argon atmosphere. The main product was isolated by column chromatography on silica-gel using benzene-acetone and identified as 5,6-dihydro-1,3-dimethyl-6-hydroxymethyluracil(2a) on the basis of its spectral data and also by the comparison with those of the authentic sample prepared photochemically(see **2-4**). The formation of dihydrodimer(3a) was also observed as a minor product, though the structure was not specified. Upon the γ-radiolysis of other

1,3-dimethyluracil derivatives(**1**b-f), the similar type of hydroxymethylation took place(Eq. 1).

The chemical yields and the G-value of the products were determined by GLC which are shown in Table 1.



(1) (2) (3)

(1)

1	R^1	R^2
1a	H	H
1b	Me	H
1c	H	Me
1d	F	H
1e	Cl	H
1f	Br	H

Table 1. γ-Irradiation of **1** in methanol.[a)]

1	R^1	R^2	Conv. /%	Product yield[b)]/% (G-value)[c)] 2	3	4[d)]	5[e)]
1a	H	H	76	77 (6.6)	2 (0.1)	0	0
1b	CH_3	H	46	47 (2.4)	11 (0.6)	0	7 (0.4)
1c	H	CH_3	12	80 (1.1)	0	0	20 (0.3)
1d	F	H	72	28 (2.3)	23 (0.9)	0	0
1e	Cl	H	63	22 (1.6)	34 (1.2)	0	0
1f	Br	H	48	3 (0.2)	0	24 (1.3)	0

a) Irradiation conditions : [1]=0.1 mol dm^{-3}, Ar saturated, room temperatue, Dose=0.1 MGy.

b) Yields are based on the amount of **1** consumed.

c) G-Value is a radiation yield : molecules/100 eV.

d) 1a : The dehalogenated product of **1**.

e) 5,6-Dihydro derivative of **1**.

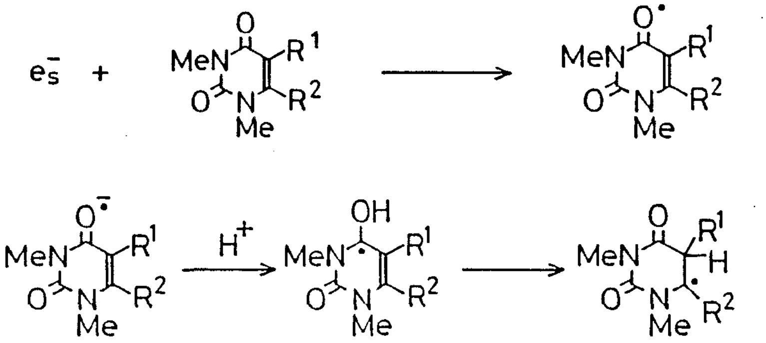
Characteristic features of these reactions are summarized as follows: (i) A regioselective hydroxymethylation at C-6 position of **1** occurs in all derivatives except for **1f**. (ii) In the case of 5-halouracils, **1d-f**, the yield of **2** decreases in the order F>Cl>Br. Consistent with this, the formation of dihydrodimer increased in **1d** and **1e**, and in the case of **1f**(Br derivative) the debromination became the main reaction, producing 1,3-dimethyluracil in the yield of 24%. In the latter case the reaction mixture was turned to acidic after irradiation. (iii) Chemical reactivity which is measured by the conversion decreased by the introduction of methyl group at C-5 and especially at C-6 of the pyrimidine. The similar trends were observed in the photochemical reactions of 1,3-dimethyluracil derivatives and was reasonably explained by the steric hindrance of the methyl group for the radical-radical coupling reactions leading to the formation of **2c** on the basis of predominant deuterium incorporation of the starting compound at C-5 position of **1c** recovered after the irradiation in methanol-OD(see **2-4**). (iv) The yields of hydroxymethylated products are rather low compared with those of the photochemical reactions. Instead of this, the formation of dimers and oligomers was observed in the γ-radiolysis.

On the basis of these observations, the Scheme 1 is proposed for the formation of **2** and 3.

The present regioselective hydroxymethylation is reasonably explained by the mechanism via the radical anion of **1** in which the radical anion subjects to a very rapid protonation and successive rearrangement of the ketyl radical to a 1,3-dimethyl-5-hydrouracil-6-yl radical(**7**).

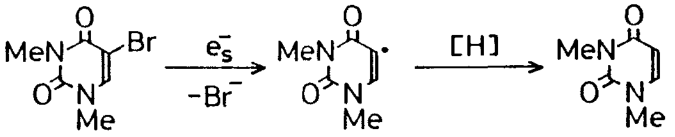
$$CH_3OH \rightsquigarrow CH_3OH^{+\cdot} + e_s^-$$

$$CH_3OH^{+\cdot} + CH_3OH \longrightarrow CH_3OH_2^+ + \cdot CH_2OH$$


(**1**$^{\cdot -}$) (**6**) (**7**)

Scheme 1.

In the case of 1,3-dimethyl-5-bromouracil(**1f**), the lifetime of bromouracil radical anions is known to be very short and the elimination of bromide ion takes place immediately after the one-elecron reduction of **1f** by solvated electron which leads to the formation of **1a**.$^{4)}$ Therefore, the main reaction of **1f** becomes debromination instead of hydroxymethylation.



Recently, similar debromination reactions of 5-bromouracil via the photochemical electron transfer have been reported by Saito et al.5) and by Swanson et al.6)

γ-Radiolysis of **1a** was also carried out in other organic solvents than methanol and the results are shown in Table 2, along with that of methanol. In all solvents investigated, the adducts of the respective solvent molecule at C-6 position of **1a**(**8**, **9**, **10**) were obtained in high yields. The structure of these compounds were determined by the spectral data and by the comparisons with those of authentic samples synthesized independently.

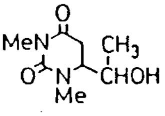
Table 2. γ-Irradiation of 1,3-dimethyluracil in several solvents.a)

		Product yieldb)/% (G-value)c)		
Solvent	Conversion/%	Adduct	Dimer(**3a**)	1,3-Dimethyl-5,6-dihydrouracil(**5a**)
MeOH	76	**2a**: 77 (6.6)	2.0 (0.1)	0
EtOH	100	**8** : 84 (9.5)	5.5 (0.3)	0
2-PrOH	87	**9** : 72 (7.0)	trace	28 (2.7)
THF	83	**10** : 73 (6.8)	trace	trace

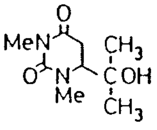
a) Irradiation conditions : [**1a**]=0.1 mol dm^{-3}, Ar saturated, room temperature, Dose=0.1 MGy.

b) Yields are based on the amount of **1a** consumed.

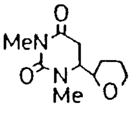
c) G-Value is a radiation yield : molecules/100 eV.



(8)



(9)



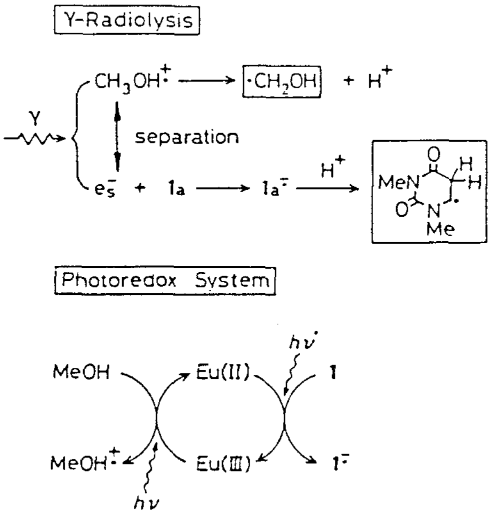
(10)

In the case of 2-propanol, the formation of 1,3-dimethyl-5,6-dihydrouracil(**11**) in addition to the adduct of 2-propanol, was significant. One of the reason of the high yield of **11** is the ease of hydrogen abstraction from 2-propanol by the intermediate radical **7**. The formation of these products(**8**, **9**, **10**) is quite reasonable because it is well-known that γ-radiolysis of these alcohols and tetrahydrofuran(THF) results in the formation of the solvent radical cation and solvated electrons, the former is transformed to α-hydroxyalkyl radical and to tetrahydrofuran-2-yl radical, respectively.

It has been reported that photoexcited 1,3-dimethyluracil adds to THF to form **10** in addtion to the regioisomer of **8**, 1,3-dimethyl-5-(tetrahydrofuran-2-yl)-5,6-dihydrouracil in approximatly equal amounts.³⁾ The photochemical reactions were explained by a radical mechanism on the basis of the non-selective addition of THF to **1a** and also the comparison with the reactions induced by the radical initiators.

Comparison with Photochemical Reactions Induced by a Eu^{III}/Eu^{II} System

In Chapter 2, it has been reported that irradiation of a methanol solution of $EuCl_3$ and 1,3-dimethyluracil through a Pyrex filter induced a regioselective hydroxymethylation in high efficiency, probably via an electron-transfer mechanism. In the present γ-radiolysis, there are similarities in reactivities of 1,3-dimethyluracil derivatives (**1**) and the main products with the photochemical reactions. However, in more detail, a regioselective hydroxymethylation takes place in an almost quantitative yield in the photochemical reactions while in the γ-radioysis the yield of the main product is not so high and the formations of dimer and dihydroproducts are also observed, especially in the cases of 5-substituted derivatives. These different behaviors in the two systems may be explained by the different distributions of primary active species initially formed as described in Scheme 2.



Scheme 2.

That is, the ionization of methanol by γ-irradiation is a very high-energy process and the ejected electrons with kinetic energy undergo solvation at a relatively far place from the parent radical cation. Accordingly, a hydroxymethyl radical derived from the methanol radical cation and a radical anion of **1**a derived from the solvated electrons are formed apart and then undergo various radical-radical reactions in homogeneous solution.

On the other hand, in the photochemical reactions, Eu^{III} catalyzes the electron-transfer from methanol to **1**a as shown in Scheme 2. Since the complexation of Eu^{III} ion with methanol and also with **1**a has been observed, the radical cation of methanol and the radical anion of **1**a are expected to be formed as the geminate pair in the vicinity. Therefore, the very efficient following reactions between the geminate pair provide the very high and selective product formation.

Experimental

Materials

1,3-Dimethyluracil(**1a**), 1,3-dimethylthymine(**1b**), 1,3,5-trimethyluacil(**1c**), 1,3-dimethyl-5-fluorouracil(**1d**), and 1,3-dimethyl-5-chlorouracil(**1e**) were synthesized from the corresponding bases by use of dimethyl sulfate. 1,3-Dimethyl-5-bromouracil(**1f**) was synthesized by the bromination of 1,3-dimethyluracil.7) All solvents were distilled over CaH_2 prior to use.

γ-Irradiation

All irradiations were carried out at the Radiation Laboratory of the Institute of Scientific and Industrial Research of Osaka University.

The sample solutions were saturated with Ar and filled in Pyrex cells and irradiated with 10 kCi ^{60}Co at room temperature. The dose rate measured by Ce dosimeter (AECL Compu-Dose System) was 6.4 kGy/h.

Analysis

All GLC analyses are made on a Shimazu GC-7A with a 1 m or 2 m glass column packed with OV-17. ^1H and ^{13}C NMR were recorded on Bruker WM-360 in $CDCl_3$ solution using TMS (tetramethylsilane) as an internal standard. Mass spectral data were obtained on a JEOL JMS-DX300 (GC, EI, and FAB mode are selectable) with a JMA-3100 data processing system.

Identification of the products

2a ; This compound was synthesized previously.$^{2)}$ Viscous oil; m/z 172 (M^+, 9%), 141 (100), 84 (88), and 42 (73); δ (^{13}C)($CDCl_3$, $SiMe_4$, off-resonance) 27.41 (q, N-$\underline{C}H_3$), 33.26 (t, C-$\underline{C}H_2$), 35.27 (q, N-$\underline{C}H_3$), 55.14 (d, N-$\underline{C}$H-), 62.09 (t, -$\underline{C}H_2$OH), 153.68 (s, $\underline{C}$=O), and 169.43 (s, $\underline{C}$=O); (^1H)($CDCl_3$, $SiMe_4$) 2.78 (m, 2H), 3.09 (s, 3H), 3.11 (s, 3H), 3.48 (m, 1H), and 3.68 (m, 2H). These values and the retention time of GLC are in agreement with those of the authentic sample which was synthesized by Eu^{III}/Eu^{II} photoredox reaction(see 2-4).

Other products were determined by direct comparison of the retention time of GLC and the Mass spectral data with the authentic samples which were synthesized by the photochemical process (see 2-4).

2b-cis; m/z 186 (M^+, 3%), 155 (100), 98 (100), 70 (81), 57 (76), 42 (98).

2b-trans; m/z 186 (M^+, 2%), 155 (100), 98 (95), 70 (62), 57 (62), 42 (98).

2c; m/z 155 (25%), 98 (11), 56 (36), 42 (12), 31 (100).

2d-cis; m/z 190 (M^+, 5%), 159 (42), 102 (75), 74 (100), 42 (44).

2d-trans; m/z 190 (M^+, 7%), 159 (64), 102 (99), 74 (100), 42 (65).

2e-cis; m/z 206 (M^+, 6%), 177 (29), 175 (88), 141 (20), 140 (34), 120 (34), 118 (100), 42 (74).

2e-trans; m/z 206 (M^+, 3%), 177 (17), 175 (54), 141 (9), 140 (17), 120 (18), 118 (60), 42 (100).

8, 9, 10 ; The structures of these compounds were determined by the ^{13}C NMR, but in the case of **10**, we obtained the different result from that of Shetlar.$^{3)}$

8-1; m/z 186 (M^+, 1%), 141 (20), 84 (17), 56 (17), 45 (100), 42 (53).

8-2; m/z 186 (M^+, 1%), 141 (18), 84 (22), 56 (30), 45 (100), 42 (91).

9; m/z 200 (M^+, 1%), 141 (71), 84 (52), 59 (48), 42 (100).

10 ; m/z (first fraction) 212 (M^+, 1%), 141 (49), 84 (57), 71 (78), 55 (57), 42 (100); m/z (second fraction) 212 (M^+, 1%), 141 (25), 84 (25), 71 (60), 55 (26), 42 (100); $\delta(^{13}C)(CDCl_3, SiMe_4$, off-resonance) 25.62 (t, C-3 or C-4 of THF), 28.25 (t, C-4 or C-3 of THF), 28.39 (q, $N\underline{C}H_3$), 32.16 (t, C-$\underline{C}H_2$), 35.98 (q, $N\underline{C}H_3$), 57.11 (d, N-$\underline{C}$H), 68.37 (t, C-5 of THF), 79.10 (d, C-2 of THF), 153.67 (s, $\underline{C}$=O), 168.90 (s, $\underline{C}$=O).

3a, 3b, 3d, and 3e : The structure of these compounds were not specified but the FAB-ionizing mass spectral data support the dimer products.

FAB-ionizing mass spectral data

1a in MeOH;	343 (2:2 adduct of **1a** and MeOH, M^++1)
	283 (dihydrodimer of **1a**, M^++1)
	203 (1:2 adduct of **1a** and MeOH, M^++1)
	173 (1:1 adduct of **1a** and MeOH, M^++1)
1a in EtOH;	371 (2:1 adduct of **1a** and EtOH, M^++1)
	231 (1:2 adduct of **1a** and EtOH, M^++1)

	187 (1:1 adduct of **1a** and EtOH, $M^{+}+1$)
1a in 2-PrOH;	401 (2:2 adduct of **1a** and 2-PrOH, $M^{+}+1$)
	201 (1:1 adduct of **1a** and 2-PrOH, $M^{+}+1$)
1b in MeOH ;	371 (2:2 adduct of **1b** and MeOH, $M^{+}+1$)
	341 (2:1 adduct of **1b** and MeOH, $M^{+}+1$)
	311 (dihydrodimer of **1b**, $M^{+}+1$)
	217 (1:2 adduct of **1b** and MeOH, $M^{+}+1$)
	187 (1:1 adduct of **1b** and MeOH, $M^{+}+1$)
1d in MeOH;	379 (2:2 adduct of **1c** and MeOH, $M^{+}+1$)
	283 (dihydrodimer of **1c**, $M^{+}+1$)
1e in MeOH;	411 (2:2 adduct of **1d** and MeOH, $M^{+}+1$)

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3-2 One-Electron Reduction of Uracil and Its 5-Substituted Derivatives - Pulse Radiolysis Study in Organic Media.

Abstract

A Pulse radiolysis study of uracil and its 5-substituted derivatives was carried out in HMPA (hexamethylphosphortriamide) solutions. The transient absorptions of uracil radical anions were observed at around 320-340 nm except 5-bromo and iodouracil. In the case of 5-chlorouracil, rapid decay of the radical anion was observed and the decay process was estimated to be the dissociation of chloride ion from the radical anion. Other undissociative radical anions provided a new absorption band at around 300 nm which is assigned to be the ketyl type radical produced by protonation of the radical anion. This protonation process was followed by a second order kinetics and the bimolecular proton transfer was estimated.

Introduction

The radiation chemistry of nucleobases has been investigated in connection with the damage of nucleic acids,1) especially a number of pulse radiolysis studies have been carried out.2) One-electron reduction of 5-halouracils were examined by a number of investigators because of the interest in the application to the radiation sensitizer of DNA.3) However, most of the investigations were focused on the aqueous solutions, where the mechanistic details were complicated by many side reactions and not yet clarified.2)

Recently, Takamuku et al. reported the dissociative electron capture of some biphenyl halides in hexamethylphosphorictriamide (HMPA) solution, in which they succeeded in the observation of the very rapid dehalogenation processes by use of the solvent and the improved pulse radiolysis system.$^{4)}$

In this chapter, the one-electron reduction of uracil band its derivatives by the pulse radiolysis method was presented.

Results and Discussion

Hexamethylphosphorictriamide (HMPA) solutions of 1 were irradiated with 8 ns electron pulses at room temperature, and the transient absorption spectra recorded at various times after the plulses are presented in Fig. 1. In the case of **1a**, **1b**, **1c**, and **1d**, the spectra observed immediately after the pulse have an absorption maxima at around 320-340 nm (band-I) which are assigned to the corresponding radical anions by comparison with those observed in aqueous system reported by Hayon.$^{2)}$ On the other hand, in the cases of **1e** and **1f**, band-I was not detected even by picosecond pulse radiolysis with 40 ps electron pulses.

Similar phenomena were also observed in the low temperature matrix experiments. After the γ-irradiation of MTHF(contained 30% of DMF) soution of **1b**, **1d**, and **1e** at 77K, band-I of **1b** and **1d** were observed but that of **1e** was not observed(Fig. 2). These observations were consistent with the fact that for **1e** and **1f**, electron capture into the σ^* level of C-halogen bond was confirmed by ESR at 77K.$^{5)}$ The radical anions of **1e** and **1f** supposed to dissociate into halide ion immediately after the

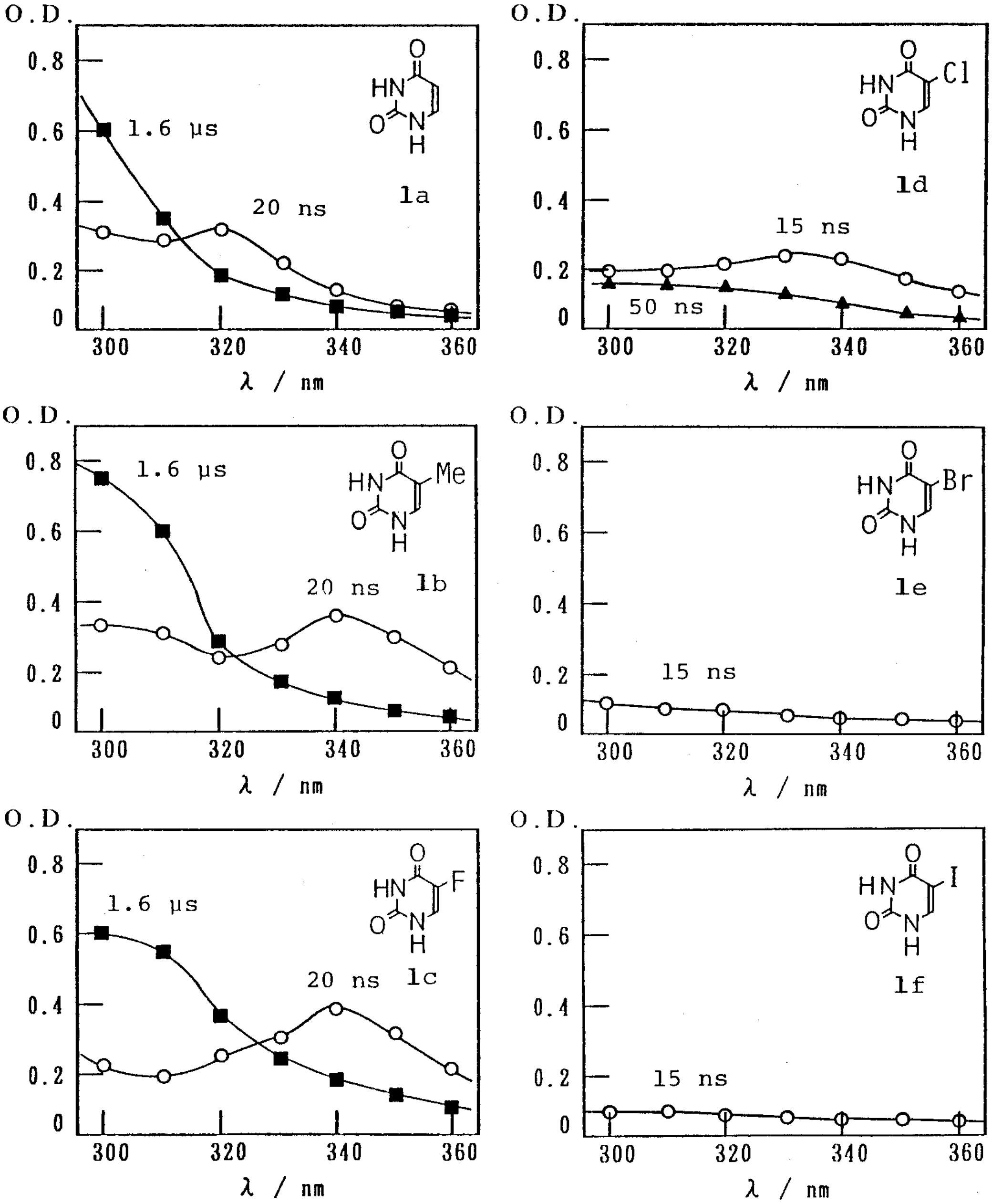


Fig. 1. Transient absorption spectra of 10 mmol dm^{-3} HMPA solutions of uracil and its 5-substituted derivatives obtained by 8 ns pulse irradiation after various times.

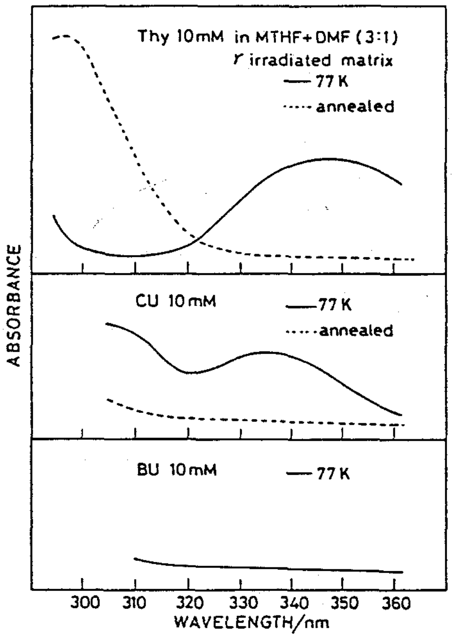
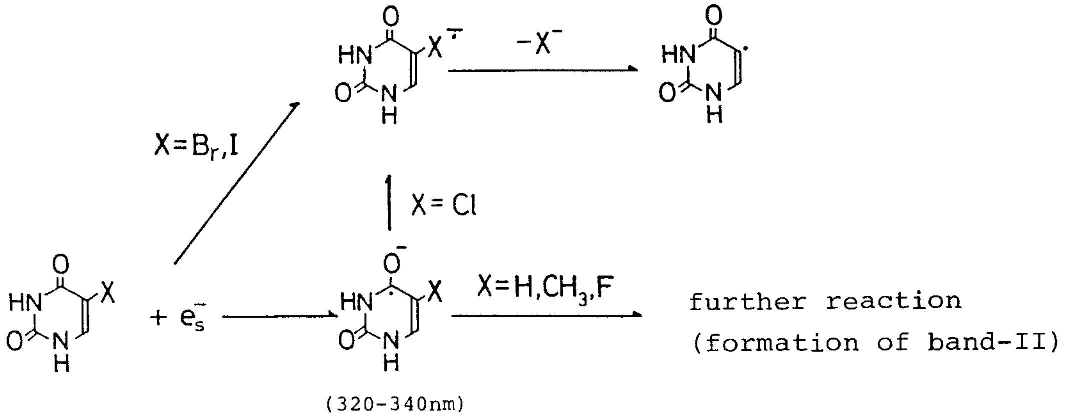


Fig. 2. Low temperature matrix spectra of **1b**, **1c**, and **1d** after γ-irradiation. [substrate]=10 mmol dm^{-3}, mixture of *MTHF and DMF* (1:3).
—— : 77 K
--- : once annealed.

electron capture but in the case of **1d**, solvated electron was captured at the carbonyl group of uracil moiety and the dechlorination occurred via an intramolecular electron transfer.

These observations were also consistent with the fact obtained by γ-irradiation as shown in the previous section, **3-1**, that 1,3-dimethyl-5-bromouracil provided 1,3-dimethyluracil as a main product.

In the cases of **1a**, **1b**, and **1c**, the decay of band-I was characterized by simultaneous formation of an absorption band at around 300 nm (band-II). The decay of band-I and the formation of band-II followed first-order kinetics and fully consistent with each other. The undissociative radical anions supposed to give band-II by the further reaction. These reaction processes were summarized in Scheme 1.



Scheme 1.

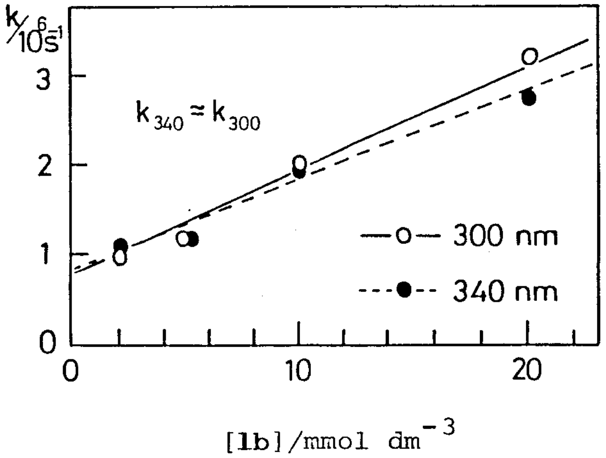
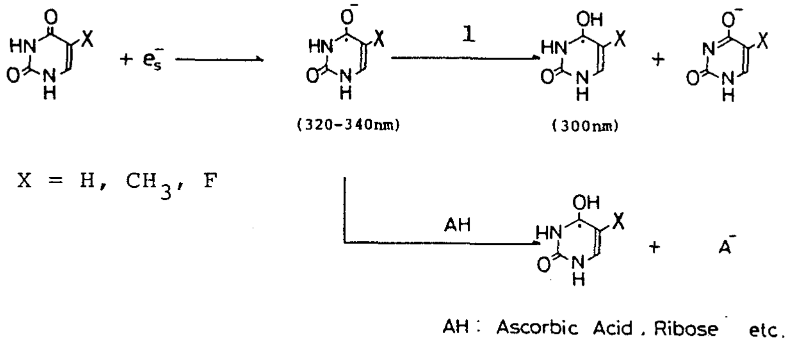


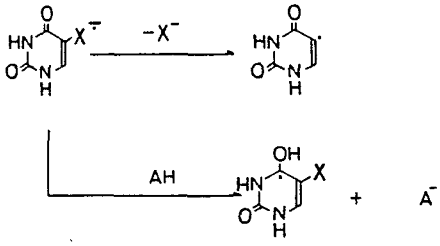
Fig. 3. Dependences of decay (340 nm: --●--) and formation (300 nm: —o—) rates on the concentration of **1b**.

Band-II was assigned as the ketyl type radical produced by protonation of the radical anion reported by Hayon.2) In HMPA solution, the protonation of radical anion by the proton transfer from HMPA radical cation supposed to be very slow because of its stability.4) The decay rate of band-I and the formation rate of band-II follwed a first order kinetics but depended on the concentration of the substrate as clearly indicated by the plot of a first order rate τ^{-1} vs. concentration of the substrate as shown in Fig. 3. The slope gave the second order rate constant: **1a**; 1.3×10^{8} $mol^{-1}dm^{3}s^{-1}$, **1b**; 1.3×10^{8} $mol^{-1}dm^{3}s^{-1}$, **1c**; 2.1×10^{8} $mol^{-1}dm^{3}s^{-1}$. This suggests that the proton donor is a neutral uracil molecule and the proton transfer reaction is a bimolecular reaction as follows.



In order to confirm the process, reactions of **1b** radical anion with several proton donors(HA) were carried out. In the case of ascorbic acid, the rate constant was very large, 3×10^9 $mol^{-1}dm^3s^{-1}$. Other proton donors also provided large rate constants: ribose; 3×10^8, sorbose 4×10^8, glucose; 5×10^8 $mol^{-1}dm^3s^{-1}$.

In the case of **1d**, dechlorination occured and the ketyl radical was not observed. However, in the previous sections **2-4** and **3-1**, the dechlorination process of chlorouracil radical anion was not observed in the photoredox system and also by γ-irradiation in MeOH. This suggests the rapid protonation of radical anions in MeOH. In fact, the ketyl radical of **1d** was observed even in HMPA by adding ascorbic acid as a strong proton donor as shown in Fig. 4. However, the ketyl radical of **1e** was not observed even by this method. Huttermann6) and Swanson7) reported the existance of the ketyl radical.



AH : Ascorbic Acid, Ribose etc.

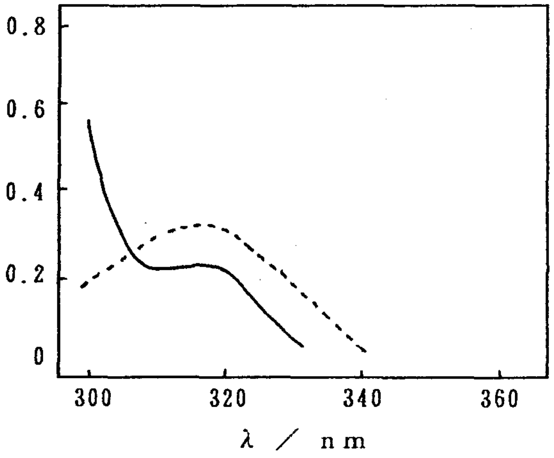


Fig. 4. Transient absorption spectra of 10 mmol dm^{-3} HMPA solutions of **1d** in the presence of ascorbic acid.

—— : [ascorbic acid]=10 mmol dm^{-3}

--- : ascorbic acid free

On the basis of these experimental observations by pulse radiolysis, the reactivity of radical anions of uracil and its derivatives has been confirmed and the results are consistent with those obtained in the previous sections 2-4 and 3-1.

Experimental

Materials

Uracil and its derivatives were obtained from Sigma Co. and Kojin Biochemical Co. available and recrystalized twice prior to use.

Hexamethylphosphorictriamide (HMPA) and dimethylformamide (DMF) were distilled twice from CaH_2 under reduced pressure.

2-Methyl-tetrahydrofuran (MTHF) was distilled over CaH_2.

Pulse Radiolysis

Sample solutions were filled in rectangular (10 mm x 10 mm) Suprasil cells and saturated with argon by bubbling for 10 minutes. Irradiations were carried out by the linear accelerator of Osaka University. The L-band linear accelerator of Osaka University was used as the source of electron pulse.4) The energy was 28 MeV and the pulse width was selected as 40 ps or 8 ns. The dose was about 100 krad per 8 ns pulse. The detection system consist of a Xe-pulse lamp (OPG-450, Osram), a monochromator (Nikon, G-250), a photomultiplier tube (Hamamatsu Photonix, R-928), a transient digitizer (Tektronix, 7912AD with 7A19 and 7B92A plug in), and a minicomputer (Melcom 70/35). The total system was shown in Fig. 5.

Low-Temperature Matrix

γ-Irradiation was carried out at the Radiation Laboratory of The Institute of Scientific and Industrial Research of Osaka University. MTHF (contained 30% DMF) was used as a matrix solvent. The sample solution was filled in a Suprasil Cell (10 mm x 1 mm) and degassed under high vacuum and then irradiated at

77K in dark. After the irradiation, absorption spectra were recorded on Hitachi 323 spectrophotometer with a Dewer vessel. The annealings were carried out by drawing up the frozen cell several seconds from the Dewer vessel.

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Chapter 4. The Reactivity of Photoexcited Eu^{II} - Fluorescence Quenching Process and Effects of Complexation

Abstract

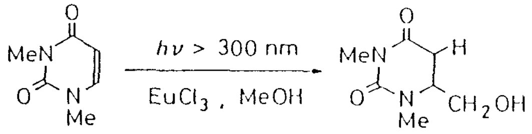
Fluorescence of Eu^{II}-crown ether complexes was quenched by 5-substituted-1,3-dimethyluracils. The quenching rate constant increased with increasing the electron-withdrawing properties of the substituents which supports the electron-transfer mechanism proposed for the Eu^{III}/Eu^{II} photoredox system. A cavity size of the crown ether also influenced the quenching process.

Introduction

I have investigated a photoredox reaction of Eu^{III} /Eu^{II} system in alcohols in the presence of an organic substrate(see Chapter 2). In this system, the reaction mechanism was found to be dependent on the substrate used. For alicyclic, aliphatic, and aromatic alkene, a radical mechanism has been proposed where hydrogen atom and hydroxymethyl radical are initially formed by the photoredox reaction of methanol and react with alkene leading to the formation of the dihydrodimer and hydroxymethylated products competitively(see **2-1** and 2-2). In the case of 1,3-dimethyluracil (**1a**), on the other hand, a regioselective hydroxymethylation of **1a** was observed in an almost quantitative yield upon irradiation (λ>300 nm) of a methanol solution of **1a** and a catalytic amount of $EuCl_3$(see 2-**4**). This reaction was reasonably explained by one-electron reduction of **1a** and successive protonation of the radical anion of **1a**, finally providing the hydroxymethylated product (2a) as shown in Scheme 1.

However, there has been no direct evidence for the electron transfer mechanism and it is not clear what controlls the reaction mechanism. In this chapter, I present the fluorescence quenching study of Eu^{II} which supports the above mechanism.

Eu^{II} is used as a luminescence material in solid states.$^{1)}$ On the other hand, in methanol solutions, the fluorescence intensity of Eu^{II}, which is a key intermediate for the hydroxymethylation, is very weak and the quenching behavior cannot be investigated. However, it has been known that the intensity is increased extremely by the addition of crown ethers.$^{2)}$ The present hydroxymethylation of **1a** was confirmed to take place efficiently even in the presence of 18-crown-6 ether. Therefore, the quenching studies are useful to elucidate the reaction mechanism. In the course of the investigation, I found a novel aspect of the quenching process influenced by a mode of complexation of Eu^{II}-crown ether depending on the cavity size.



(1a) 100 mmol·dm^{-3} (2a) 98 %

Results and Discussion

The laser irradiation (308 nm, 15 ns, 100 mJ) of a methanol solution of $EuCl_3$ (10 mmol dm^{-3}) and a crown ether (100 mmol dm^{-3}) resulted in the oxidation of methanol and the corresponding formation of Eu^{II} which reached a photostationary state after about 60 pulses irradiation. The formation of Eu^{II} was confirmed by its absorption spectrum,[2,3] and also by the fluorescence spectrum,[2] as shown in Figs. 1 and 2. In the case of 15-crown-5, the intensity was much strong and the lifetime was longer than that of 18-crown-6, and blue shifts of both spectra were observed. However, without crown ether, the fluorescence was very weak and the lifetime was very short as shown in Fig. 3. In this case, the lifetime was measured by a single photon counting method.

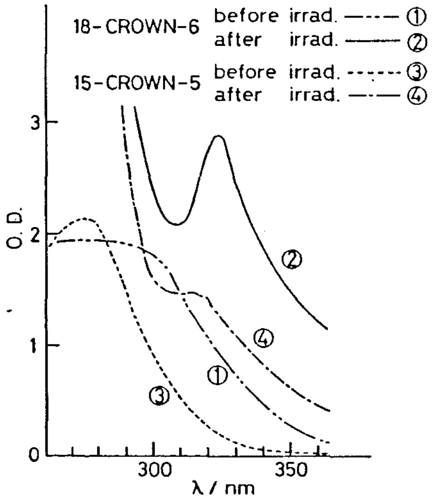


Fig. 1. Absorption spectra of methanol solutions of $EuCl_3$ containing crown ethers before and after 60 pulses laser irradiation.
[$EuCl_3$ $6H_2O$]=10 mmol dm^{-3}, [crown ether]=100 mmol dm^{-3}, Ar saturated, at room temperature.

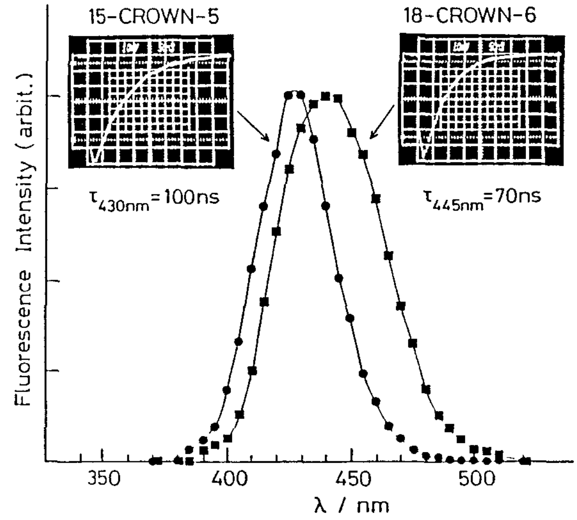
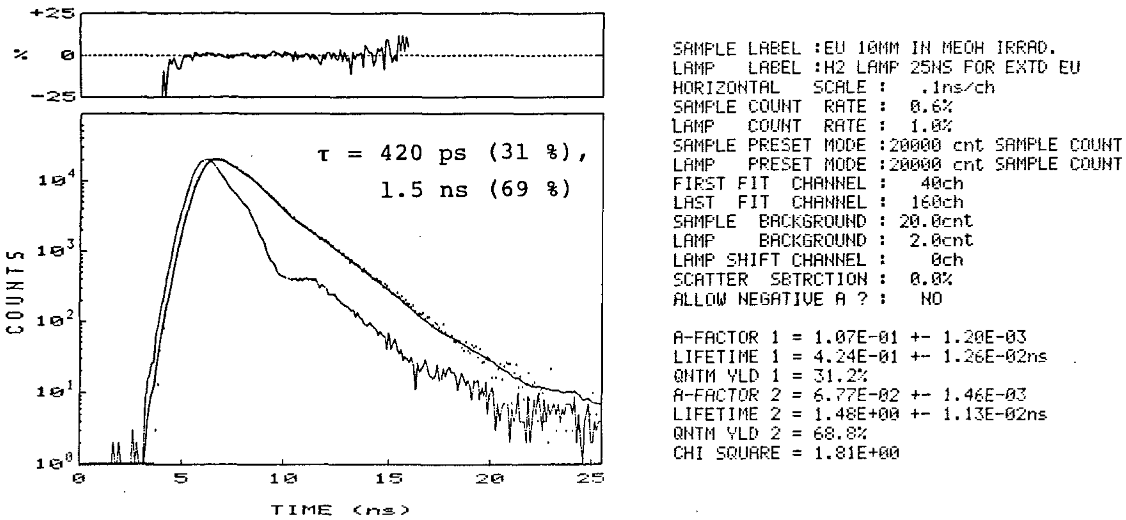


Fig. 2. Transient emission spectra of methanol solutions of $EuCl_3$ containing crown ethers.
The sample solutions are the same to those used in Fig. 1. Inserts show the decay profiles of both emissions.



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LAMP   LABEL :H2 LAMP 25NS FOR EXTD EU
HORIZONTAL   SCALE :   .1ns/ch
SAMPLE COUNT  RATE :  0.6%
LAMP   COUNT  RATE :  1.0%
SAMPLE PRESET MODE :20000 cnt SAMPLE COUNT
LAMP   PRESET MODE :20000 cnt SAMPLE COUNT
FIRST FIT  CHANNEL :   40ch
LAST  FIT  CHANNEL :  160ch
SAMPLE  BACKGROUND : 20.0cnt
LAMP    BACKGROUND :  2.0cnt
LAMP SHIFT CHANNEL :    0ch
SCATTER  SBTRCTION :  0.0%
ALLOW NEGATIVE A ? :   NO

A-FACTOR 1 = 1.07E-01 +- 1.20E-03
LIFETIME 1 = 4.24E-01 +- 1.26E-02ns
QNTM YLD 1 = 31.2%
A-FACTOR 2 = 6.77E-02 +- 1.46E-03
LIFETIME 2 = 1.48E+00 +- 1.13E-02ns
QNTM YLD 2 = 68.8%
CHI SQUARE = 1.81E+00
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Fig. 3. The fluorescence lifetime of Eu^{II} obtained by a single-photon counting. $[EuCl_3]=10$ mmol dm^{-3}, Ar saturated methanol solution, 15 min. preirradiated with a high pressure mercury lamp.

Table 1. Effect of crown ether to the photoreaction of uracils.[a)]

Substrate	R	Crown Free Conv./%	Crown Free Yield/%	+ 18-Crown-6 Conv./%	+ 18-Crown-6 Yield/%
1a	H	91	97	66	99
1b	CH_3	88	91	91	99
1c	F	64	67	93	89
1d	Cl	71	57	100	80*

R: The substituent at C-5 position of 1,3-dimethyluracil. [**1**]=100 mmol dm^{-3} ([**1d**]=50 mmol dm^{-3}), $[EuCl_3]=10$ mmol dm^{-3}, [18-crown-6]=0.1 mol dm^{-3}, Ar saturated MeOH solution, 6 h irrad. Yields are based on the amounts of **1** consumed.

* The product was a methanol adduct of **1a**; dechlorinated one

The fluorescence quenching of Eu^{II}-crown complexes by **1** was also carried out by laser flash photolysis of a methanol solution of $EuCl_3$ and the crown ether which was pre-irradiated to the photostationary state in the presence of changing amounts of **1**.

A plot of the reciprocal of the fluorescence lifetime against the concentration of **1** provides the quenching rate constant(k_q) (Fig. 4). In all derivatives, the rate constants were very large, $>10^8$ $mmol^{-1}dm^3s^{-1}$ and the substituent effect suggested the charge transfer character of the quenching process. The rate constants for α-methylstyrene for which a radical mechanism has been proposed(see **2-1** and 2-2), is very low; 4.6×10^7 $dm^3mol^{-1}s^{-1}$ (18-crown-6 complex) and $\leq10^6$ $dm^3mol^{-1}s^{-1}$ (15-crown-5 complex). In the cases of alicyclic olefins, no quenching was observed. These observations are consistent with the reaction mechanism which has been presumed from the product analysis (see **2-1** and 2-2).

To confirm the quenching process, the quenching rate constants obtained with **1** are plotted against the Hammett σ_p as shown in Fig. 4. The rate constant increases with increasing the electron-withdrawing properties of the substituents, suggesting the electron transfer character of the quenching process. The introduction of an electron-withdrawing substituent makes the pyrimidine ring electron deficient and lowers the reduction potential,4) thus leading to an acceleration of the electron transfer quenching.

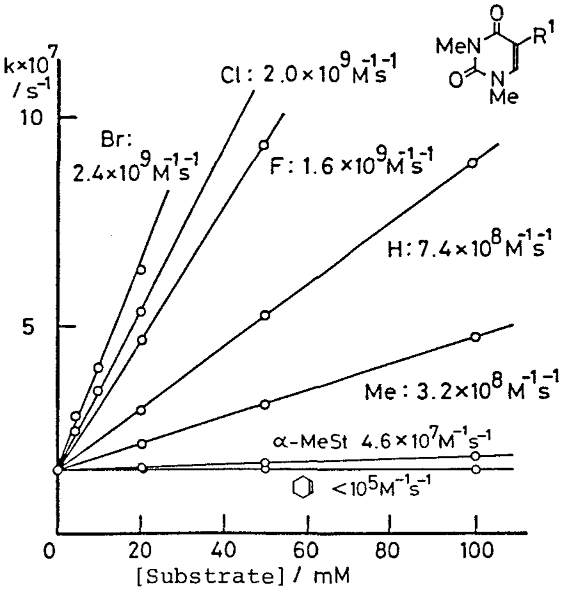


Fig. 4. The fluorescence quenching of Eu^{II}-18-crown-6 complex by 5-substituted-1,3-dimethyluracils. $[EuCl_3]$=10 mmol dm^{-3}, [18-crown-6]=0.1 mol dm^{-3} methanol solution, Ar saturated, 60 pulses preirradiated with a XeCl excimer laser.

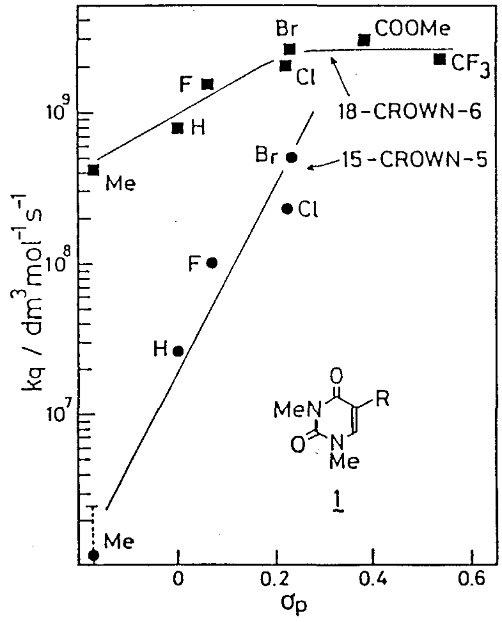
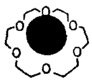


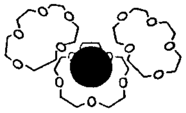
Fig. 5. Hammett plot of the quenching rate constants (k_q) of Eu^{II}-crown complexes by 5-substituted-1,3-dimetyluracils.

Another interesting finding is the effect of the cavity size of the crown ether on the quenching behavior. The quenching rate costants for Eu^{II}-18-crown-6, are very large and near diffusion-controlled, while Eu^{II}-15-crown-5 provides rather small rate constants but a high ρ value of the Hammett plot is obtained.

This novel behavior of the quenching process may correlate with the significant effect on the fluorescence intensity by the complexation. Adachi et al. suggested that the complexation inhibited the collision quenching of photoexcited Eu^{II} by solvent molecule leading to the increasing of the fluorescence intensity. Furthermore, the fluorescence intensity of 15-crown-5 complex is stronger than that of 18-crown-6 complex because the former is proposed to be a 1:3 complex and the collisional quenching is sterically more hindered than the latter which is proposed to be a 1:1 complex.$^{5)}$ The quenching process of photoexcited Eu^{II} by **1** may be influenced by the effects of complexation.

	Fitness	Emission		k_q
		Lifetime	Intensity	
18-crown-6	loose	short	weak	large
15-crown-5	rigid	long	strong	small


18-crown-6


15-crown-5

Experimental

Materials

1,3-Dimethyluracil, 1,3-dimethylthymine, 1,3-dimethyl-5-fluorouracil, 1,3-dimethyl-5-chlorouracil, 1,3-dimethyl-5-trifluoromethyluracil, and methyl 1,3-dimethyl-isoorotate were synthesized by methylation of corresponding bases obtained from TCI Co. and Sigma Co. with dimethyl sulfate. 1,3-dimethyl-5-bromouracil was synthesized by bromination of 1,3-dimethyluracil with bromine water.6)

Crown ethers were obtained from TCI Co. and used without purifications.

Methanol was distilled over CaH_2 prior to use.

Instruments

Laser Flash Photolysis System

The laser flash photolysis system was consist of an excimer laser (Lamda Physik, EMG-501), a monochrometor (Nikon, G-250), a photomultiplier tube (Hamamatsu Photonix, R-928), a storage oscilloscope (Tektronix, 7834 with a 7A24 and a 7B80 plug in), and a synchronizing unit (Mori Enginiering). The transient signals were recorded by Polaroid films.

EMG-501 was used as a XeCl excimer laser. Its oscilating wavelength was 308 nm, pulse width was 15 ns, and output power was about 100 mJ.

Single Photon Counting System

The single photon counting system was consists of an optical unit [PRA(Photochemical Research Associates), 510 lamp unit, 1211 gas handling unit, 510B high voltage power supply, 1611 monochromertor drive unit, Jobin-Yvon H.10C monochrometor] and a electronix unit (Horiba, NAES-1100 Time-Resolved Spectrofluorophotometer).

Steady State Spectral Analysis

Absorption spectra and fluorescence spectra were recorded on a Hitachi 323 spectrophotometer and a Hitachi 850 spectrofluorophotometer, respectively.

Sonication

Sonications were carried out with a Bransonic B32H ultrasonic cleaner.

Procedure

A reaction mixture was filled in a Suprasil cell (10 mm x 10 mm) and degassed by sonication for 5 minutes and saturated with Ar by bubbling for 10 minutes and then irradiated.

Single-photon counting measurements were carried out with the reaction mixtures which were pre-irradiated withe the laser to the photostationary state.

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Conclusion

The results obtained from the present investigation can be summarized as follows;

Chapter 1: The photoredox reaction by use of europium ions was investigated in organic solvents. On illumination of a methanol solution of $EuCl_3$ $6H_2O$ through a Pyrex filter resulted in the formation of hydrogen and also oxidation products of methanol, ethylene glycol and formaldehyde. Similar hydrogen evolution was observed in other solvents and the ethanol solution provided about 4 times amount of hydrogen than that of the methanol solution. This reaction was initiated by the CT-excitation of Eu^{III}-methanol which induced the formation of Eu^{II}. Thereafter, Eu^{II} became the main light-absorbing species and promoted hydrogen evolution and this system showed a very high turnover number. Other europium salts were also investigated and hydrogen evolution was observed in the case of $Eu(ClO_4)_3$, although, the degradation of ClO_4^- was observed.

Chapter 2: The synthetic applications of the Eu^{III}/Eu^{II} photoredox reaction by use of various substrates were investigated.

i) Photoirradiation of a methanol solution of α-methylstyrene in the presence of $EuCl_3$ through a Pyrex filter resulted in the formation of its dihydrodimer and a 1:1 methanol adduct in high yields. Similar reactions were observed in other aromatic alkenes but the yields were rather low. This reaction was induced by the addition of hydrogen atom and hydroxymethyl radical produced by a Eu^{III}/Eu^{II} photoredox system in methanol. The radical mechanism was confirmed by the experiments in ethanol, 2-propanol, and deuterium labelled methanols.

ii) Photoirradiation of a methanol solution of $EuCl_3$ and alkene such as cyclohexene, cyclooctene, cyclododecene, and tetramethylethylene gave 1:1 adduct of methanol as a main product. This reaction proceeded via a radical mechanism similar to that of aromatic alkenes. The hydrogen abstraction from methanol was a key reaction and the concentration of alkene influenced the products distribution.

iii) The effective hydroxyalkylation of malonic acid diesters was observed in the Eu^{III}/Eu^{II} photoredox system. Photoirradiation of a methanol solution of dimethyl malonate and $EuCl_3$ resulted in the formation of dimethyl hydroxyethyl malonate and its lactone, 2-methoxycarbonyl-γ-butyrolactone. Similar reaction was also observed in the case of diethyl malonate. The two-step reaction mechanism was suggested in which hydroxyalkylation and successive formation of alkene by dehydration occurred, thereafter, the second step hydroxyalkylation occured to provide the final products.

iv) Photoirradiation of a methanol solution of $EuCl_3$ and 1,3-dimethyluracil through a Pyrex filter induced a regioselective hydroxymethylation at C-6 position in high efficiency via an electron transfer mechanism. Similar addition of solvent was observed in ethanol, 2-propanol, and tetrahydrofuran solution. The electron transfer mechanism was confirmed by the selective incorporation of deuterium at C-5 position which was observed in the irradiation of the CH_3OD solution and also by the dechlorination which was observed in the prolonged irradiation of 1,3-dimethyl-5-chlorouracil.

Chapter 3: One electron reduction of uracil and its derivatives induced by the irradiation of ionizing radiation. The synthetic approach was carried out with γ-irradiation and the mechanistic approach was carried out by a pulse radiolysis technique.

i) γ-Radiolysis of 1,3-dimethyluracil and its derivatives in methanol solution resulted in the regioselective hydroxymethylation at C-5 position. Analogous additions of ethanol, 2-propanol, and tetrahydrofuran to 1,3-dimethyluracil occurred in high efficiency. A mechanism via the one-electron reduction was presented, although it was slightly different from that of the photoredox reaction in more details. In this system, the yiels were not so high and the formations of dimer and dihydro products were also observed which were explained by the different distributions of primary active species initially formed in the two different reaction systems.

ii) The pulse radiolysis study of uracil and its derivatives elucidated the reactivities of the radical anions. The transient absorptions of uracil radical anions were observed except for 5-bromo and 5-iodouracil and in the case of 5-chlorouracil, rapid decay of the radical anion was observed and the decay process was estimated to be the dissociation of chloride ion from the radical anion. Other undissociative radical anions provided the ketyl type radicals by protonation and this process was followed by a second order kinetics and the bimolecular proton transfer was suggested. These observations were consistent with the results obtained in the photoredox system and the γ-irradiation system.

Chapter 4: Fluorescence of Eu^{II} which was enhanced by the aid of crown ethers was quenched effectively by 1,3-dimethyluracils. In 5-substituted uracils, the quenching rate constant increased with increasing the electron withdrawing properties of the substituents and no quenching was observed by alicyclic alkenes. These observations supported the mechanisms suggested in Chapter 2. A cavity size of the crown ether also influenced the quenching process.

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