

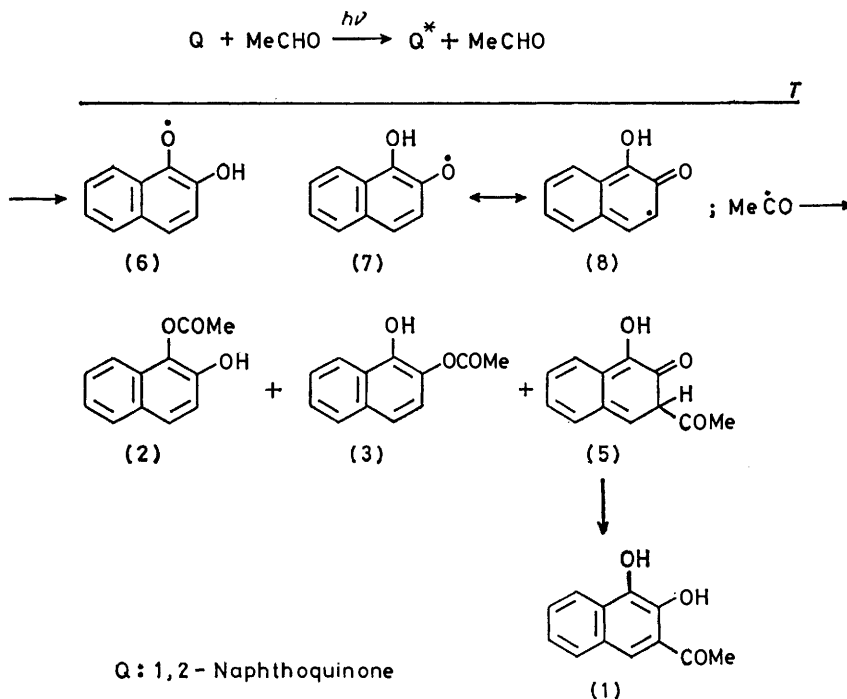
Mechanism of Light-induced Reductive Acetylation of 1,2-Naphthoquinone with Acetaldehyde¹

By Kazuhiro Maruyama, Department of Chemistry, Faculty of Science, Kyoto University, Kyoto 606, Japan
Akio Takuwa,* Shigeo Matsukiyo, and Osamu Soga, Department of Chemistry, Faculty of Science, Shimane University, Matsue 690, Japan

The detailed mechanism of the photochemical reaction of 1,2-naphthoquinone with acetaldehyde has been investigated. From a study of the reaction using the ¹H CIDNP technique and change of the product distribution with temperature, it was deduced that the almost all parts of the reaction proceed *via* an 'in-cage' mechanism at a low temperature, but at 20 °C at least 6.7% of the reaction proceeds *via* an 'out-of-cage' mechanism. For comparison, the addition of thermally generated acetyl radical to 1,2-naphthoquinone has also been examined.

THERE have been many investigations of the light-induced reactions of quinones with aldehydes in literature.² In general, reductive acylation products are reported to be formed. As for the mechanisms of these light-induced reductive acylations two have been postulated. One is an 'in-cage' mechanism, *i.e.*, the

hyde although no evidence was produced for this.⁴ On the other hand, for the formation of 2-acetylhydroquinone in the light-induced reaction of 1,4-benzoquinone with acetaldehyde, Bruce and Cutts have suggested the addition of acetyl radical to 1,4-benzoquinone in ground state (*i.e.*, an out-of-cage mechanism)



SCHEME 1

process involving the intervening contribution of initial radical pair, and the other is an 'out-of-cage' mechanism, *i.e.*, the process involving the addition of free acyl radical to quinone in its ground state. We proposed recently an in-cage mechanism for the photochemical reactions of phenanthrene-9,10-quinone with a variety of aldehydes, in which reactions 9-acyloxy-10-hydroxyphenanthrenes were produced extremely clean.³ Similarly, an in-cage mechanism was tentatively proposed for the formation of 2-acetylnaphthalene-1,4-diol in the photolysis of 1,4-naphthoquinone and acetalde-

hyde followed by subsequent enolization to give the final products.⁵

We recently reported the photo-induced reductive acylations of 1,2-naphthoquinones with aliphatic aldehydes.⁶ In the reactions 3-acylnaphthalene-1,2-diols and naphthalene-1,2-diol monoacyl esters were the major products. Schemes 1 and 2 outline possible reaction mechanisms: *i.e.*, Scheme 1 illustrates an in-cage mechanism and Scheme 2 an out-of-cage mechanism.

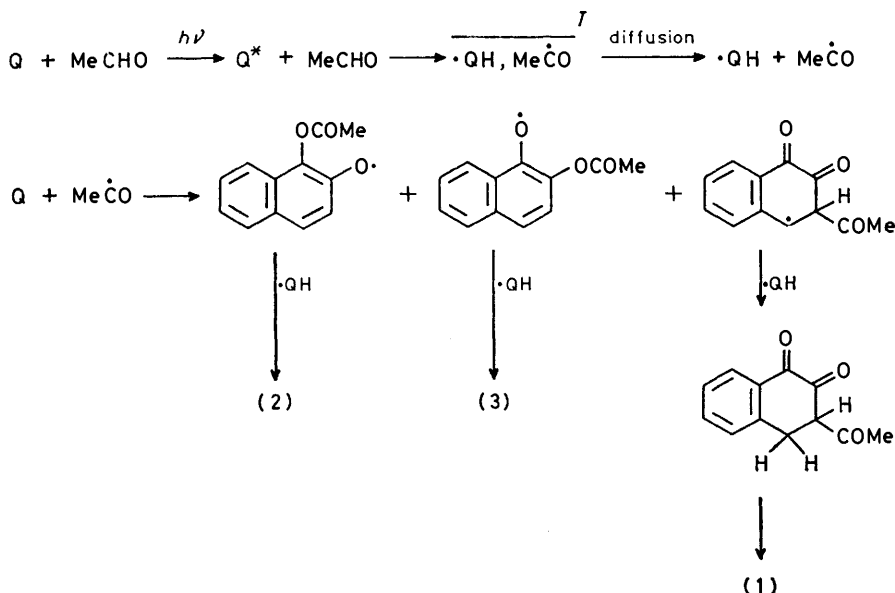
In order to determine the true mechanism, the ¹H CIDNP technique was applied to the reaction. In

addition, acetyl radical generated by hydrogen abstraction from acetaldehyde was allowed to react with 1,2-naphthoquinone, and the resulting products were compared with those of the photochemical reaction. Further, detailed analyses of the variation of product distribution with temperature change gave a good insight into the reaction.

RESULTS AND DISCUSSION

Irradiation ($>340 \text{ nm}^*$) of 1,2-naphthoquinone in acetaldehyde or in a benzene solution of acetaldehyde

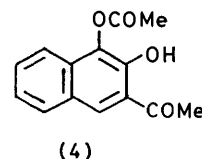
shift of hydroxy-proton and i.r. spectrum indicated the presence of intramolecularly hydrogen-bonded hydroxy and carbonyl groups. Thus, structure (4) was assignable to the product, *i.e.* 1-acetoxy-2-hydroxy-3-acetylnaphthalene. The acetylation product of (4) with acetic anhydride was identical with the authentic 3-acetyl-1,2-diacetoxynaphthalene^{6b} which was obtained from the acetylation of (1). Light-induced reaction of 3-acetyl-1,2-naphthoquinone with acetaldehyde gave additional support for structure (4) in that the same product was formed.



SCHEME 2

at 15–20 °C gave 3-acetylnaphthalene-1,2-diol (1) (*C*-acetylated product, 24%) and a mixture of naphthalene-1,2-diol monoacetates (2) and (3) (*O*-acetylated product, 39%).⁶ The other 1,2-naphthoquinones (4-cyano, 6-bromo, and 6-methyl derivatives) behaved similarly in the reaction with aliphatic aldehydes (propanal, butanal, and pentanal, *etc.*) to give the corresponding 3-acetylnaphthalene-1,2-diols and naphthalene-1,2-diol monoacyl esters.⁶

At the outset of our mechanistic investigations, we re-examined the product distribution in the photolysis of 1,2-naphthoquinone and acetaldehyde at 22 °C. In addition to *C*-acetylated product (22%) and *O*-acetylated product (34%) reported so far, we isolated a further minor, but mechanistically very important, product as yellow prisms (0.9%). The i.r. spectrum of this product indicated the presence of hydroxy (ν_{max} , 3 410 cm^{-1}) and carbonyl (ν_{max} , 1 762 and 1 661 cm^{-1}) groups whilst the ¹H n.m.r. spectrum showed signals at δ 2.22 (3 H, singlet, OCOCH₃), 2.64 (3 H, singlet, COCH₃), 7.04–7.95 (4 H, multiplet, aromatic protons), and 11.33 (1 H, singlet, OH, exchanged with D₂O). Both the chemical



A possible route in the photochemical reaction of 1,2-naphthoquinone with acetaldehyde to give reductive acetylation products could involve the geminate combination of an initially formed radical-pair consisting of 1,2-naphthosemiquinone and acetyl radicals in a solvent cage (see Scheme 1). Since ¹H CIDNP signals provide invaluable information for investigating such a radical-pair process,⁸ the photochemical reaction

was examined by this technique. Spectra (a), (b), and (c) in Figure 1 correspond respectively to ¹H n.m.r. spectra observed before, during, and after irradiation. In spectrum (b), three singlet polarized-emission signals (signals 1, 2, and 3), doublet polarized-emission signals (signal 4), and polarized-absorption/emission signals (signal 5) can be recognized. Signals 2 (δ 1.8) and 3 (δ 2.0) in spectrum (b) correspond to the methyl protons of *O*-acetylated product (2 and 3). Comparing the spectra (b) with (c), we find that signals 1 (δ 1.4), 4 (δ 4.1),

* Filter solution: a aqueous solution of 2,7-dimethyl-3,6-diazacyclohepta-2,6-diene perchlorate (1 cm path-length of 0.26 g l⁻¹).⁷

and 5 (δ 5.8–6.5) in (b) are absent in (c). These signals therefore may be assigned to an unstable intermediate [*i.e.* structure (5)] as indicated in (b) which could be enolized to *C*-acetylated product (1). Actually, both *C*-acetylated product (signal 6) and *O*-acetylated product (signals 2 and 3) are accumulated in the reacting mixture as indicated in spectrum (c).

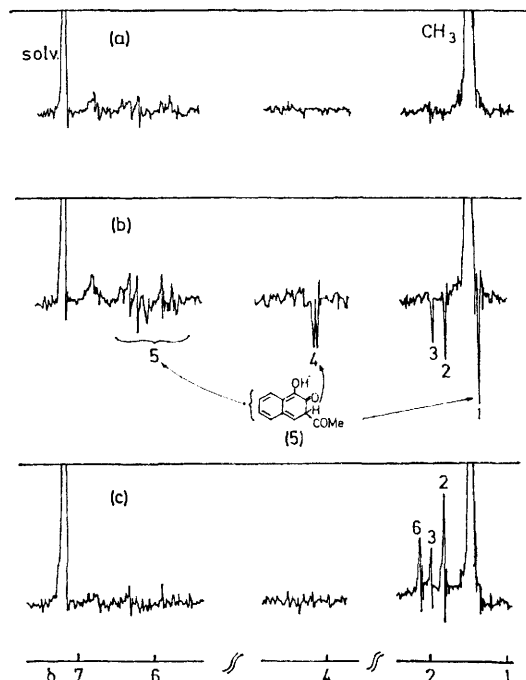


FIGURE 1 ^1H N.M.R. spectra observed for the photochemical reaction of 1,2-naphthoquinone with acetaldehyde in $[^2\text{H}_6]$ benzene at 25 °C: (a) before irradiation; (b) during irradiation; (c) after irradiation

Since the polarized signals due to 1-acetoxy-2-hydroxy-3-acetylnaphthalene (4), however, could not be observed in spectrum (b), the pathway for the formation of (4) should be different from those of *C*- and *O*-acetylated products.

Kaptein's equation,⁹ (i), allows us to predict the net effect of polarization, Γ ne.

$$\Gamma ne = \Delta g \cdot \epsilon \cdot \mu \cdot a_i \quad (\text{i})$$

These parameters have their usual meaning. As to the polarized-emission signals 1, 2, and 3 in Figure 1(b), $\Delta g = -$, $\epsilon = +$, and $a_i = +$ are assignable, because (2), (3), and (5) are the geminate combination products, the g -value of 1,2-naphthosemiquinone radical is in general larger than that of carbon radical without exception, and hyperfine coupling constant a_i of acetyl radical is $+5.3$ G.¹⁰ Thus, in equation (i), $- = - + \mu +$, then μ must be positive, suggesting formation of a triplet radical pair.

Taking into consideration the results of ^1H CIDNP, we may conclude that reductive acetylation products may arise *via* the following pathway. 1,2-Naphthoquinone molecule excited to the $n\pi^*$ singlet state is converted into the triplet state *via* intersystem crossing;¹¹ the

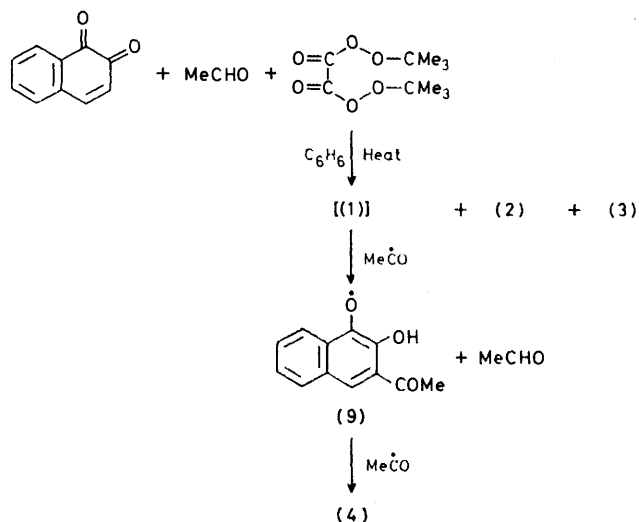
excited quinone molecule in the triplet state abstracts hydrogen from acetaldehyde to give a triplet radical-pair consisting of 1,2-naphthosemiquinone and acetyl radicals in a solvent cage. From the two possible resonating structures (6) and (7) or 1,2-naphthosemiquinone radical, products (2) and (3) could be derived through *in-cage* combination with acetyl radical. As another possible route 1,2-naphthosemiquinone radical (8) combines with acetyl radical to give an unstable intermediate (5) which is easily enolizable to yield (1). These processes are summarized in Scheme 1.

In general, in the ^1H CIDNP experiment fairly large polarized signals resulting from a combination product can be observed, even if a minor portion of the reaction proceeds with a radical-pair process.¹² Therefore, the signal intensity of ^1H CIDNP signal does not reflect directly the portion of the radical-pair process involved in the reaction.

To determine the true portions of the *in-cage* (Scheme 1) and the *out-of-cage* processes (Scheme 2), the 'forced' addition reaction of free acetyl radical to 1,2-naphthoquinone was undertaken. Treatment of a benzene solution of 1,2-naphthoquinone and acetaldehyde with di-*t*-butyl peroxyoxalate¹³ (DTBP) in the dark allowed us to generate the necessary reacting conditions. When decomposition of DTBP (4 mmol) was carried out at 36 °C in a benzene solution (30 ml) of 1,2-naphthoquinone (2 mmol) and acetaldehyde (40 mmol), 1-acetoxy-2-hydroxy-3-acetylnaphthalene (4) and the *O*-acetylated products (2)/(3) were isolated in yields of 6.5 and 1%, respectively. Repeated re-examination of the same reaction under similar conditions constantly resulted in the formation of (4) as major product. In addition, 6-bromo-1,2-naphthoquinone behaved similarly in the thermal addition reaction with acetyl radical to give 1-acetoxy-2-hydroxy-3-acetyl-6-bromonaphthalene and 6-bromonaphthalene-1,2-diol monoacetates, in yields of 8 and 6%, respectively. The results described above suggest that almost all the (4) obtained in the photochemical reaction comes from the *out-of-cage* process. Of course, a small part of the *O*-acetylated product obtained in the photolysis could also be formed *via* the *out-of-cage* process.

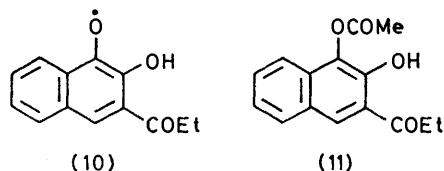
The following two observations confirm that compound (4) comes only from the *out-of-cage* process. A benzene solution of *C*-acetylated product and acetaldehyde was treated with DTBP to give (4) in 7% yield; similar treatment of *O*-acetylated product led to quantitative recovery of starting material. The results suggest that (4) may arise only *via* *C*-acetylated product as shown in Scheme 3. Further support for this possibility was provided by the following competitive reactions; a benzene solution of 1,2-naphthoquinone (0.5 mmol), 3-propionynaphthalene-1,2-diol^{6b} (0.5 mmol), and DTBP (0.25 mmol) was kept in the dark at room temperature and then worked up to give only one product, *i.e.* 1-acetoxy-2-hydroxy-3-propionynaphthalene (11). However, when a two molar quantity of DTBP (0.5 mmol) was used, (11) was obtained as the major product

with only a small amount of (4). These results strongly indicate that free acetyl radical preferentially abstracts hydrogen from 3-propionynaphthalene-1,2-diol to leave a phenoxyl radical (10) and acetaldehyde rather than attacking 1,2-naphthoquinone. The phenoxyl radical



(9) or (10) may react again with free acetyl radical to give (4) or (11) as formulated in Scheme 3.

Determining the amounts of the products from the in-cage and the out-of-cage process allows an estimate of the extent of each. Further the variations of the product distributions in the photochemical reaction were examined at various temperatures. After samples containing a benzene solution of 1,2-naphthoquinone and acetaldehyde were irradiated for 2 h at 4, 22, 50,



70, and 90 °C using the same light source, the products were separated by t.l.c. and the yields determined by ^1H n.m.r. analysis; the results are given in the Table and Figure 2.

A plot of the product yields *vs.* the reaction temperature gives a straight line for the temperatures examined (Figure 2). The yields of *C*-acetylated product decrease with increasing temperature, but those of both *O*-acetylated product and (4) increase. These results also strongly support the view that the *C*-acetylated product is produced from an in-cage process whilst (4) and a small portion of *O*-acetylated product are produced from an out-of-cage process. In fact, the decrease in the amount of *C*-acetylated product at temperatures above 4 °C is in fair agreement with the increment of both (4) and *O*-acetylated product at the same temperature as compared with the amounts of these at 4 °C (see Figure 2). Since at 4 °C the amount

of (4) is too small to be determined, it is reasonable to consider that the reaction mostly proceeds (>99.9%) *via* an in-cage process at this temperature (see also Figure 3). Therefore, for example, the comparison of amount of decrease of *C*-acetylated product of 20 °C against the yield at 4 °C indicates the amount of dif-

The relative yields of the products obtained from the photochemical reactions of 1,2-naphthoquinone with acetaldehyde at various temperatures ^a

Product	Temperature (± 1 °C)				
	4	22	50 ^b	70 ^b	90 ^b
(1)	1.19	1.00 ^c	0.69	0.54	0.30
(2) + (3)	1.30	1.46	1.68	1.78	1.96
(4)	trace ^d	0.05	0.13	0.17	0.24

^a 1,2-Naphthoquinone (0.24 mmol) and acetaldehyde (12 mmol) in 12 ml of benzene. ^b Total amounts of the products decrease with increasing temperature owing to partial decomposition of the quinone with increasing temperature. ^c 10.8 mg. ^d The yield was too small to be determined by ^1H n.m.r. analysis, but the formation was recognized with t.l.c.

fusion of the initially formed radical-pair out of solvent cage at this temperature. We can thus estimate the relative portion (6.7%) of the in-cage and the out-of-cage processes at 20 °C from the ratio of the amount of decrease of *C*-acetylated product against the yield of it at 4 °C to the total yields of the products, *i.e.* (1), (2), (3), and (4), at the temperature. Portions of the out-of-cage process

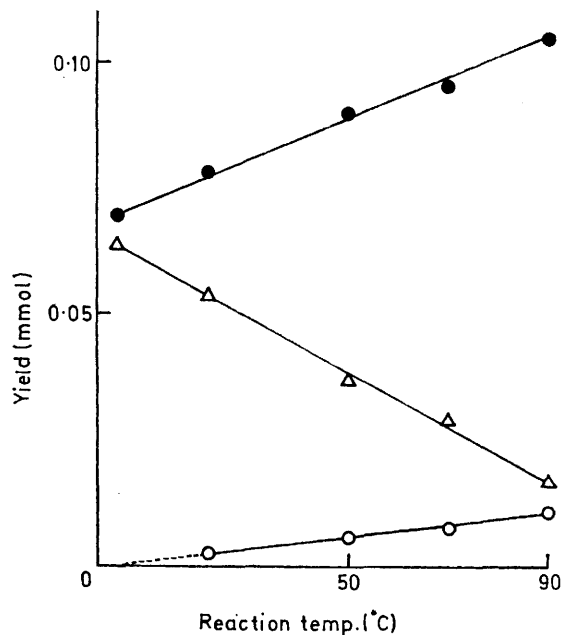


FIGURE 2 Temperature dependence of the products of: *C*-acetylated product (1) (Δ), *O*-acetylated product (2) + (3) (\bullet), and 1-acetoxy-2-hydroxy-3-acetylnaphthalene (4) (\circ)

involved in the reaction were estimated analogously as 7.7, 19.4, 27.8, and 36.3% at 22, 50, 70, and 90 °C, respectively (see Figure 3).*

In conclusion, the mechanism of the light-induced

* On the basis of these calculations we postulated that (i) the number of photons absorbed in reactant is constant, and (ii) with temperature change the amount of initially formed radical-pair stays constant.

(1.5 mmol), DTBP (1 mmol), and acetaldehyde (200 mmol) was kept in the dark at 40 °C for 7 days. After work-up, the following two products were obtained: 1-acetoxy-3-acetyl-6-bromo-2-hydroxynaphthalene (37 mg), as yellow needles, m.p. 173—174 °C (Found: C, 52.65; H, 3.49. $C_{14}H_{11}BrO_4$ requires C, 52.04; H, 3.43%), ν_{max} 3 420, 1 776, and 1 660 cm^{-1} ; $\delta(CCl_4)$ 2.43 (3 H, s, $OCOCH_3$), 2.66 (3 H, s, $COCH_3$), 7.43—7.84 (4 H, aromatic protons), and 11.40 (1 H, s, exchanged with D_2O), and 6-bromo-naphthalene-1,2-diol monoacetates (25 mg) which were identical with authentic samples.^{6a,b}

(e) A benzene solution (25 ml) of 6-bromo-1,2-naphthoquinone (2 mmol), DTBP (2 mmol), and acetaldehyde (100 mmol) was refluxed in the dark for 30 min. Work-up afforded 53 mg of the former product and 49 mg of the latter product in (d).

(f) A benzene solution (20 ml) of 3-acetylnaphthalene-1,2-diol (1) (1 mmol), DTBP (0.5 mmol), and acetaldehyde (50 mmol) was kept in the dark at 30 °C for 9 days. Work-up afforded (4) (12 mg) and unchanged (1) (68 mg).

(g) A benzene solution (20 ml) of naphthalene-1,2-diol monoacetates (2) and (3) (1 mmol), DTBP (0.5 mmol), and acetaldehyde (50 mmol) was kept in the dark at 30 °C for 9 days; (2) and (3) were recovered almost quantitatively (195 mg).

(h) A benzene solution (20 ml) of 1,2-naphthoquinone (0.5 mmol), 3-propionynaphthalene-1,2-diol^{6b} (0.5 mmol), DTBP (0.25 mmol), and acetaldehyde (50 mmol) was kept in the dark at 30 °C for 7 days. Separation of product by t.l.c. gave 1-acetoxy-2-hydroxy-3-propionynaphthalene (11) (5 mg), yellow prisms, m.p. 130—131 °C (Found: C, 69.5; H, 5.45. $C_{14}H_{12}O_4$ requires C, 69.76, H, 5.46%), ν_{max} 1 760 and 1 658 cm^{-1} ; $\delta(CCl_4)$ 1.22 (3 H, t, J 7.0 Hz, CH_3), 2.44 (3 H, s, $OCOCH_3$), 3.06 (2 H, q, J 7.0 Hz, $COCH_2$), 7.24—8.12 (5 H, ArH), and 11.68 (1 H, s, OH, exchanged with D_2O); m/e 258 (M^+ , trace), 215 (100), 197 (29), and 186 (33).

(i) A benzene solution (20 ml) of 1,2-naphthoquinone (0.5 mmol), 3-propionynaphthalene-1,2-diol (0.5 mmol),

DTBP (0.5 mmol), and acetaldehyde (50 mmol) was kept in the dark at 30 °C for 7 days. Separation of products by t.l.c. gave (4) (5.9 mg) and (11) (20.2 mg).

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REFERENCES

- Presented in part at the 26th IUPAC Congress, Tokyo, September 1977.
- (a) A. Schönberg, G. O. Schenck, and O. A. Neumuller, 'Preparative Organic Chemistry,' Springer-Verlag, New York, 1968; (b) J. M. Bruce, *Quart. Rev.*, 1967, **21**, 405; (c) J. M. Bruce, 'Photochemistry of Quinones' in 'The Chemistry of the Quinonoid Compounds,' ed. S. Patai, John Wiley & Sons, 1974, Part I, p. 465.
- (a) K. Maruyama, A. Takuwa, T. Otsuki, and S. Kako, *Bull. Inst. Chem. Res., Kyoto Univ.*, 1972, **50**, 348; (b) K. Maruyama, H. Sakurai, and T. Otsuki, *Bull. Chem. Soc. Japan*, 1977, **50**, 2777.
- G. O. Schenck and G. Koltzenburg, *Naturwiss.*, 1954, **41**, 452.
- J. M. Bruce and E. Cutts, *J. Chem. Soc. (C)*, 1966, 449.
- (a) K. Maruyama and A. Takuwa, *Chem. Letters*, 1974, 471; (b) A. Takuwa, *Bull. Chem. Soc. Japan*, 1976, **49**, 2790; (c) A. Takuwa, *ibid.*, 1977, **50**, 2973.
- S. L. Murov, 'Handbook of Photochemistry,' Marcel Dekker, New York, 1973, p. 99.
- S. H. Pine, *J. Chem. Educ.*, 1972, **49**, 664, and references cited therein.
- R. Kaptein, *Chem. Comm.*, 1971, 732; *J. Amer. Chem. Soc.*, 1972, **94**, 6251.
- H. Fisher, 'Structure of Free Radicals by E.S.R. Spectroscopy,' in 'Free Radicals,' ed. J. A. Kochi, John Wiley & Sons, New York, 1973, Vol II, p. 444.
- K. Maruyama, A. Takuwa, and O. Soga, *J.C.S. Perkin II*, 1979, 255.
- H. R. Ward, 'Chemically Induced Dynamic Nuclear Polarization,' in 'Free Radicals,' ed. J. A. Kochi, John Wiley & Sons, New York, 1973, Vol. I, p. 270.
- P. D. Bartlett, E. P. Benzing, and R. E. Pincock, *J. Amer. Chem. Soc.*, 1960, **82**, 1762.
- G. Schwarzenbach and K. Lutz, *Helv. Chim. Acta*, 1940, **23**, 1339.
- H. J. Teuber and N. Göts, *Chem. Ber.*, 1954, **87**, 1236.
- K. Maruyama, T. Otsuki, A. Takuwa, and S. Arakawa, *Bull. Chem. Soc. Japan*, 1973, **45**, 2470.