

# The Rates of Termination of Radicals in Solution. III.<sup>1</sup> Semidione Radicals

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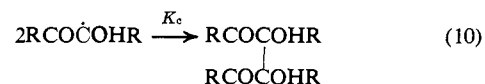
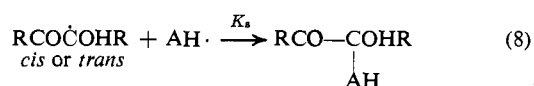
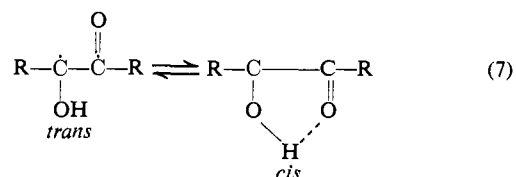
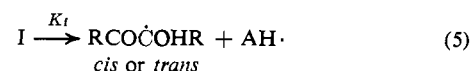
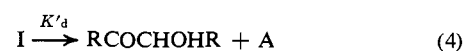
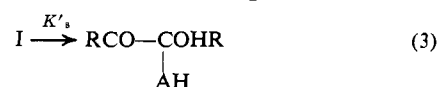
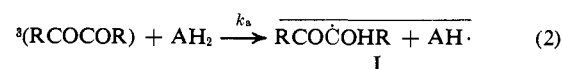
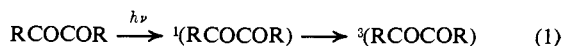
**Abstract:** The bimolecular radical decay rates for the semidione radicals derived from a series of nine  $\alpha$ -diketones have been determined in isopropyl alcohol by a light intermittency-esr technique. Two classes of radicals are recognized: those derived from rigidly *cis*, sterically hindered  $\alpha$ -diketones (1-4), which decay by disproportionation and have decay rate constants about  $1-4 \times 10^7 M^{-1} \text{sec}^{-1}$ , and those derived from flexible  $\alpha$ -diketones, which terminate by coupling and show decay rates about  $2-4 \times 10^{-8} M^{-1} \text{sec}^{-1}$ .

The reduction of  $\alpha$ -diketones to yield radical anions<sup>4</sup> and neutral radicals has been extensively investigated.<sup>5-10</sup> Our interest in the latter stems from our attempts to establish structure-reactivity relationships for the rates of radical termination reactions.<sup>1,11,12</sup> Although many investigations of the photoreactions of  $\alpha$ -diketones have appeared,<sup>13</sup> little work has been done on the termination rates of the intermediate radicals.<sup>6,10</sup>

Since the semidione radicals can exist in *cis* and *trans* forms<sup>14,15</sup> and the radicals may terminate *via* coupling, disproportionation, or reaction with a radical derived from the solvent, the reaction scheme is necessarily complex. Scheme I, where R may be alkyl or aryl, overlines indicate "caged" species, and AH<sub>2</sub> is the solvent, gives the steps which may be important in the reaction of these radicals. All of the nonradical-producing reactions of the photoexcited states (*i.e.*, fluorescence, phosphorescence, etc.) have been omitted. In addition the scheme has been simplified by making the two R groups equivalent. If they are different, the possible reactions of two different radicals plus an equilibrium between them must be considered.

Examination of the products of photoreductions shows that some of the reactions are not important in particular systems. Products derived from the coupling of a semidione radical with a solvent radical are found when the reaction is carried out in methanol,<sup>10,13</sup> in xylene,<sup>16</sup> or in aldehydes.<sup>17,18</sup> However, in isopropyl

## Scheme I



alcohol, the solvent in which most of our work was carried out, no products formed by the coupling of the semidione radical with solvent radicals have been observed.<sup>10,13,18,19</sup> Although it is conceivable that some termination in the solvent may occur by reactions 3 and 8 to yield cross-coupling products which decompose to the observed products by some molecular process, it is unlikely that this would contribute greatly to the observed decay. Under our experimental conditions, in

(1) Part II: S. A. Weiner and G. S. Hammond, *J. Amer. Chem. Soc.*, in press.

(2) American Chemical Society, Petroleum Research Fund Fellow, 1968-1969.

(3) National Institutes of Health Postdoctoral Fellow, 1967-1968.

(4) G. A. Russell, E. T. Strom, E. R. Talaty, K. Y. Chang, R. D. Stevens, and M. C. Young, *Rec. Chem. Progr.*, **27**, 3 (1966), and references cited therein.

(5) G. Porter and M. W. Windsor, *Proc. Roy. Soc., Ser. A*, **245**, 238 (1958).

(6) A. Beckett, A. D. Osborne, and G. Porter, *Trans. Faraday Soc.*, **60**, 873 (1964).

(7) H. Zeldes and R. Livingston, *J. Chem. Phys.*, **47**, 1465 (1967).

(8) R. J. Pritchett, *Mol. Phys.*, **12**, 481 (1967).

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(10) B. M. Monroe and S. A. Weiner, *J. Amer. Chem. Soc.*, **91**, 450 (1969); B. M. Monroe, S. A. Weiner, and G. S. Hammond, *ibid.*, **90**, 1913 (1968).

(11) S. A. Weiner and G. S. Hammond, *ibid.*, **90**, 1659 (1968).

(12) S. A. Weiner and G. S. Hammond, *ibid.*, **91**, 986 (1969).

(13) G. E. Gream, J. C. Paice, and C. C. R. Ramsay, *Aust. J. Chem.*, **20**, 1671 (1967), contains a summary of  $\alpha$ -diketone photoreactions.

(14) G. A. Russell and R. D. Stevens, *J. Phys. Chem.*, **70**, 1320 (1966).

(15) G. R. Luckhurst and L. E. Orgel, *Mol. Phys.*, **7**, 297 (1963).

(16) M. B. Rubin and R. G. LaBarge, *J. Org. Chem.*, **31**, 3283 (1966).

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(18) W. H. Urry and D. J. Trecker, *J. Amer. Chem. Soc.*, **84**, 118 (1962).

(19) W. G. Bentrude and K. R. Darnall, *Chem. Commun.*, 810 (1968).

which the signal-to-noise ratio was generally greater than 10:1 no signal for the acetone ketyl radical was observed. Hence, if cross coupling were taking place, it would account for less than 10% of the decay we observe. In addition, the cross-coupling products would be unsymmetrical pinacols. Since the symmetrical pinacols produced from the irradiation of biacetyl<sup>19</sup> and benzophenone<sup>20</sup> in isopropyl alcohol and the unsymmetrical pinacol from the irradiation of camphorquinone in methanol are stable to the reaction conditions and easily isolated, there is no reason to believe that cross-coupling products, if formed, would not have been found in the product mixtures. For these reasons we feel that reactions 3 and 8 need not be considered in our discussion of radical decay in isopropyl alcohol.

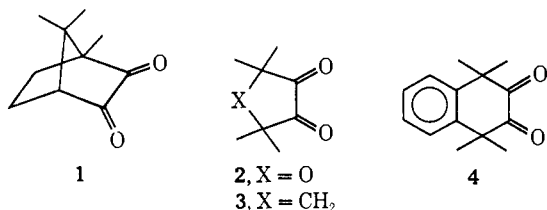
### Experimental Section

**Materials.** Biacetyl (Aldrich), benzil (Matheson Coleman, and Bell), *d*-camphorquinone (1) (Eastman), and 1-phenyl-1,2-propanedione (Aldrich) were all commercial materials. Toluil (6),<sup>21</sup> anisil (7),<sup>21</sup> 1,1,4,4-tetramethyl-2,3-dioxotetralin (4),<sup>22</sup> and tetramethyl-3,4(2H,5H)-furanedione (2)<sup>23</sup> were prepared by methods reported in the literature. The 3,3,5,5-tetramethyl-1,2-cyclopentanedione (3) was a gift from Professor P. A. Leermakers. All solvents were spectroscopic grade and were used without further purification.

**Measurement of Decay Constants.** All solutions were about 0.1 *M* in diketone or saturated solutions, if the diketone was not soluble to 0.1 *M*. The apparatus and procedures used in determining the decay kinetics have been briefly described,<sup>10-12</sup> and will be discussed in detail in a forthcoming publication devoted to experimentation in this field.<sup>24</sup> As discussed previously, an error of  $\pm 20\%$  is associated with a given termination constant.<sup>11,12</sup>

### Results and Discussion

**Observation of the Semidione Radicals.** The semidione radicals were generated by irradiation of degassed isopropyl alcohol solutions of the  $\alpha$ -diketones in the cavity of the esr spectrometer. In some cases the esr signals from the radicals could be resolved. The semidione radical derived from camphorquinone (1) has already been described.<sup>10</sup> Tetramethyl-3,4(2H,5H)-furanedione (2) gave a strong signal which could be resolved into nine lines with a line spacing of 0.13 G (Figure 1). These are the inner nine lines of the thirteen-line splitting pattern produced by coupling of the unpaired electron with the twelve equivalent protons on the four methyl groups. The outer four lines are too weak to be observed since the intensities of these lines are predicted to be in the ratio 1:12:66:220:495:792:924:729:495:220:66:12:1. The carbon analog, 3,3,5,5-tetramethyl-1,2-cyclopentanedione (3), gave a



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(21) M. Weiss and M. Appel, *ibid.*, **70**, 3666 (1948).

(22) L. R. C. Barclay, C. E. Milligan, and N. D. Hall, *Can. J. Chem.*, **40**, 1664 (1962).

(23) I. K. Korobitsyna, Yu. K. Yur'ev, and O. I. Nefedova, *Zh. Obshch. Khim.*, **24**, 188 (1954); *Chem. Abstr.*, **49**, 3197a (1955).

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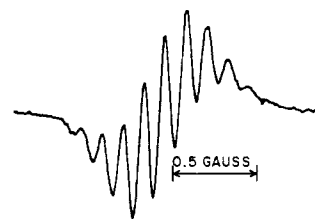
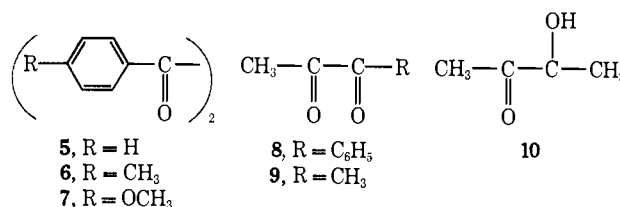


Figure 1. High-resolution esr spectrum of 2 irradiated in isopropyl alcohol.

similar spectrum, but it was not completely resolved. No coupling with the hydroxyl proton of either radical was observed.

The semidione radical derived from 1,1,4,4-tetramethyl-2,3-dioxotetralin (4) was observed as a sharp singlet in isopropyl alcohol, even under conditions at which splittings as small as 0.1 G would have been observed. However, irradiation of 4 in *p*-xylene gave a doublet signal whose line spacing was 2.40 G, indicating coupling with the hydroxyl hydrogen. Further, irradiation of 1 in *p*-xylene gave a very complex, unsymmetrical signal which was probably the overlapping signals of the two possible semidione radicals. Therefore, it must be concluded that in isopropyl alcohol the semidione radicals derived from 1-4 fail to show coupling with the hydroxyl hydrogens since these protons are rapidly exchanging with the solvent, a process which is not possible in xylene. The symmetrical signal which is observed from the camphorquinone ketyl radical in isopropyl alcohol can be attributed to this rapid exchange of the hydroxyl proton with the solvent, rather than internal exchange between the two carbonyl groups as had been previously proposed.<sup>10</sup>

Benzil (5), toluil (6), anisil (7), and 1-phenyl-1,2-propanedione (8) gave relatively weak, symmetrical signals, that could not be resolved. However, at our instrument settings, couplings less than about 3 G would not have been observed, so it is not possible to determine if the hydroxyl hydrogen is exchanging with the solvent or not.



The signal from the semidione of biacetyl 10 was partially resolved and was consistent with the more highly resolved spectrum of Zeldes and Livingston.<sup>7</sup> These authors assigned splitting constants of 13.41 G to the protons of one methyl group, 2.58 G to the protons of the other methyl group, and 2.07 G to the hydroxyl proton.

The radical derived from biacetyl 10 shows a hydroxyl coupling of 2.07 G while those derived from ketones 1-4 show no measurable coupling. Apparently this is because the latter exchanges with the solvent (*vide infra*) while the former does not, although the possibility that the hydroxyl hydrogen of the rigidly *cis* semidione radicals has a very small or zero coupling constant cannot

be ruled out entirely.<sup>25,26</sup> At present there seems to be no good explanation for this difference.

**Radical Termination Rates.** The termination rates for the ketyl radicals derived from nine  $\alpha$ -diketones were measured in isopropyl alcohol solution. These values are shown in Table I. The numbers given for cam-

**Table I.** Decay of Ketyl Radicals in Isopropyl Alcohol Solution

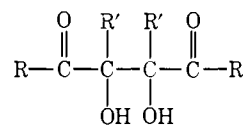
Compound	$[R]_0 \times 10^{+6} M$	$K_t[R]_0 \times 10^{-2} \text{ sec}^{-1}$	$K_t \times 10^{-7} M^{-1} \text{ sec}^{-1}$
Camphorquinone (1)	6.6	2.6	3.9
	5.2	2.0	3.9
	7.3	3.5	4.8
4	7.6	3.2	4.2
	3	9.4	1.5
2	10.0	1.5	1.5
	7.8	1.2	1.6
	10.0	3.2	3.2
Biacetyl (9)	2.2	8.6	39.0
	10	0.78	2.7
Benzil (5)	0.59	2.0	34.0
	6	0.64	2.1
Toluil (6)	0.89	1.9	21.0
	7	0.71	1.8
Anisil (7)	1.4	5.9	42.0

phorquinone indicate the precision of the measurements.<sup>27</sup> These rates are a measure of radical disproportionation (eq 9), radical coupling (eq 10), or both, since other termination processes such as cross coupling are unimportant in isopropyl alcohol.<sup>10,13,18,19</sup>

It is apparent that the termination constants fall into two groups whose values differ roughly by a factor of ten. The "slower group" contains the four rigidly *cis*- $\alpha$ -diketones, 1-4, while the faster group consists of the flexible  $\alpha$ -diketones, 5-9. The photochemistry of two of the rigidly *cis*- $\alpha$ -diketones, camphorquinone (1)<sup>10</sup> and 1,1,4,4-tetramethyl-2,3-dioxotetralin (4),<sup>13</sup> has been studied. In each case only products derived from radical disproportionation (eq 9) were observed. No pinacol-type dimer, the expected product of radical coupling, was observed. Although the photochemistry of 2 and 3 has not been studied, analogous products would be expected because of their structural similarity to 1 and 4. Therefore, the radical termination rates of the ketyl radicals derived from compounds 1-4 are rates of radical disproportionation (eq 9) rather than of coupling (eq 10), unless a dimer is formed which goes to the observed product by a nonradical process. They are of the same order of magnitude as those of the semiquinone radicals derived from *p*-quinones, such as benzoquinone ( $K_t = 5.7 \times 10^7 M^{-1} \text{ sec}^{-1}$ ),<sup>1</sup> which presumably also decay by disproportionation.

The "faster group" contains the ketyl radicals derived from the flexible, unhindered  $\alpha$ -diketones. Photoreduction of biacetyl in isopropyl alcohol gives a quantitative yield of the pinacol 11.<sup>19</sup> Irradiation of benzil in ethanol or ether also produces a pinacol 12,<sup>28</sup> which is

thermally unstable and forms benzil in solution in the presence of oxygen.<sup>28,29</sup> Although a complete product analysis from an irradiation of benzil in isopropyl alcohol has not yet been reported, Bunbury and Wang have reported that 12 precipitates from an irradiated solution of degassed isopropyl alcohol.<sup>30,30a</sup> Therefore, although we cannot be certain that coupling is the sole method of termination in isopropyl alcohol, we believe it to be the major pathway. However, it should be recognized that our measured rate constants may include both coupling and disproportionation. Although the photoreduction of 1-phenyl-1,2-propanedione has not been studied, chemical reduction has been reported to yield a pinacol (13).<sup>31</sup> The substituted benzils have not been studied, but their photoreactions should be similar to that of benzil. Thus, as far as is known, coupling rather than disproportionation is the principal, and possibly sole, manner of termination for the radicals derived from these  $\alpha$ -diketones. These values are of the same order of magnitude as termination rates for the ketyl radicals derived from benzophenones ( $K_t$  for benzophenone =  $1.1 \times 10^8 M^{-1} \text{ sec}^{-1}$ )<sup>1</sup> which couple rather than disproportionate.



11, R = R' = CH<sub>3</sub>

12, R = R' = C<sub>6</sub>H<sub>5</sub>

13, R = CH<sub>3</sub>; R' = C<sub>6</sub>H<sub>5</sub>

Therefore, two classes of  $\alpha$ -diketone ketyl radicals can be recognized. One class consists of those derived from the rigidly *cis*, sterically hindered  $\alpha$ -diketones (1-4) which decay by disproportionation rather than by coupling and whose decay rates are about  $1-4 \times 10^7 M^{-1} \text{ sec}^{-1}$ . The second group contains those formed from flexible  $\alpha$ -diketones which terminate by coupling rather than disproportionation and whose termination rates are about  $2-4 \times 10^7 M^{-1} \text{ sec}^{-1}$ .

Previous work from these laboratories has shown that there is a large substituent effect on the rates of decay of the ketyl radicals derived from substituted benzoquinones and benzophenones which was correlated by the  $\sigma$  values for the substituents.<sup>1</sup> However, a regular substituent effect was not observed for a series of substituted cumyl radicals generated from photolysis of azo compounds.<sup>12</sup> Although the number of compounds is too limited to draw any firm conclusion, examination of the bimolecular decay rate for benzil and the two substituted benzils indicates that there is probably not a large, regular substituent effect on the decay of ketyl radicals derived from benzils.

From studies of the flash photolysis of benzil, Beckett, Osborne, and Porter have reported a value of  $4.11 \times 10^5 \text{ sec}^{-1}$  for the decay of the benzil ketyl radical.<sup>6</sup>

(29) D. L. Bunbury and C. T. Wang, *Can. J. Chem.*, **46**, 1473 (1968)

(30) Reference 29, note 3.

(30a) NOTE ADDED IN PROOF. An analysis of product mixtures from the irradiation of benzil in isopropyl alcohol has appeared (D. L. Bunbury and T. T. Chuang, *Can. J. Chem.*, **46**, 1473 (1968). Complex product mixtures containing 12 and several other products are reported. However, from the data given it is not possible to determine if all these products are primary reaction products or arise from further irradiation of 12.

(31) T. Arai, *Denki Kagaku*, **30**, 175 (1962); *Chem. Abstr.*, **62**, 15760g (1965).

(25) H. Zeldes and R. Livingston, *J. Chem. Phys.*, **45**, 1946 (1966).

(26) R. Wilson, *J. Chem. Soc., B*, 84 (1968).

(27) The  $K_t$  for camphorquinone was originally reported<sup>10</sup> to be  $1.6 \times 10^7$ . Careful redetermination of the decay gives the indicated values.

(28) H. Klinger, *Chem. Ber.*, **19**, 1862 (1886); G. Ciamician and P. Silber, *ibid.*, **34**, 1530 (1901); A. Benrath, *J. Prakt. Chem.*, **87**, 416 (1913); W. D. Cohen, *Chem. Weekblad*, **13**, 590 (1916).

This value together with our value for the decay of benzil ketyl gives  $\epsilon = 8.0 \times 10^2 M^{-1} \text{ cm}^{-1}$  at  $\lambda_{\text{max}}$  490 nm.

As mentioned above, irradiation of **1** in *p*-xylene gave an epr spectrum apparently due to a mixture of the two semidione radicals. The total steady-state radical concentration was  $6.1 \times 10^{-6} M$  and a  $k_t$  of  $8.7 \times 10^7 M^{-1}$  was calculated on the basis of a single radical being present. Since the irradiation of **1** in *p*-xylene has been shown to yield primarily cross-coupling product (eq 8), plus smaller amounts of product derived from coupling of solvent radicals (eq 11), and disproportionation of the camphoquinone semidione radical (eq 10),<sup>16</sup>

this constant is a weighted average of several different rate constants.

**Acknowledgments.** It is a pleasure to acknowledge the help and encouragement provided by Professor George S. Hammond. We thank Professor J. D. Roberts for the use of his CAT 400, Professor P. A. Leermakers for his generous gift of 3,3,5,5-tetramethyl-1,2-cyclopentanedione, and Drs. Chin-Hua Wu and Emerson Sanford for the gift of various compounds used in this study. This work was supported by the Directorate of Chemical Sciences, Air Force Office of Scientific Research, Contract No. AF 49(638)-1479.

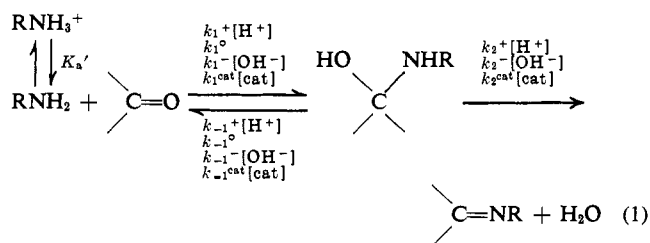
## General Base Catalysis of Thiosemicarbazone Formation<sup>1</sup>

Jane M. Sayer and William P. Jencks

Contribution No. 670 from the Graduate Department of Biochemistry, Brandeis University, Waltham, Massachusetts 02154. Received July 3, 1969

**Abstract:** Thiosemicarbazone formation from *p*-chlorobenzaldehyde exhibits a change in rate-determining step at about pH 4, similar to that in semicarbazone formation, with rate-determining amine attack below and rate-determining dehydration above this pH. The attack step is subject to general acid catalysis by carboxylic acids with a Brønsted coefficient  $\alpha = 0.15$ . It is also subject to base catalysis. The dehydration step provides the first reported example of general base catalysis of this class of reaction. A number of bases of different structure and charge type follow a Brønsted line of slope 0.71. The reverse reaction is formulated as an attack of hydroxide ion on the free imine which is subject to general acid catalysis. The solvent deuterium isotope effects,  $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$ , are 3.2 and 2.6 for catalysis by triethylenediamine and 3-quinuclidinol, respectively, whereas  $k_{\text{OH}^-}/k_{\text{OD}^-}$  is 1.05. The dehydration step is subject to general acid catalysis by phosphate and dimethylmalonate monoanions, as well as by the solvated proton. The isotope effect,  $K_{\text{H}_2\text{O}}/K_{\text{D}_2\text{O}}$ , on the ionization constants as acids of both thiosemicarbazide ( $\text{p}K_{\text{aH}_2\text{O}}' = 12.81$ ) and *p*-chlorobenzaldehyde thiosemicarbazone ( $\text{p}K_{\text{aH}_2\text{O}}' = 11.20$ ) is  $4.0 \pm 0.1$ .

Base catalysis of oxime formation was noted by Auwers<sup>2</sup> and was examined quantitatively by Barrett and Lapworth, who proposed that the reaction involves the attack of the hydroxylamine anion on the carbonyl group.<sup>3</sup> More recent work has shown that this catalysis, and the similar catalysis for semicarbazone and O-methyl oxime formation, involves acceleration by hydroxide ion of the dehydration of the tetrahedral intermediate that is in equilibrium with starting materials above neutral pH ( $k_2^-$ , eq 1).<sup>4</sup> In general, this type of



reaction proceeds with rate-determining attack of amine on the carbonyl compound at low pH and undergoes a

change in rate-determining step to acid- and base-catalyzed dehydration of the tetrahedral addition intermediate as the pH is increased (eq 1).<sup>5</sup> Williams and Bender observed an inverse isotope effect for catalysis of oxime formation by hydroxide ion and suggested that the reaction involves specific base catalysis.<sup>6</sup> The present investigation was carried out in an attempt to determine whether this catalysis represents specific or general base catalysis and to examine other aspects of the mechanism of thiosemicarbazone formation.

### Experimental Section

**Materials.** Reagent grade inorganic salts were used without further purification. Organic acids and bases (with the exception of reagent grade formic and acetic acids) were purified by recrystallization, distillation, or sublimation. Final purification of *p*-chlorobenzaldehyde was effected by sublimation, after recrystallization from ethanol-water. The purified aldehyde was stored in the cold in the presence of a desiccant. Thiosemicarbazide was recrystallized twice from water. Glass-distilled water was used in all experiments.

Stock solutions of *p*-chlorobenzaldehyde were prepared in ethanol and were stored at 4°. These were diluted on the day of use with water containing sufficient disodium ethylenediaminetetraacetate to give a concentration of  $10^{-4} M$  in the final reaction mixture. The ethanol concentration in the final reaction mixtures was less than 0.2%. Dilute aqueous solutions of *p*-chlorobenzaldehyde were kept under argon to prevent possible air oxidation of the al-

(1) Supported by grants from the National Science Foundation (GB 4648) and the National Institute of Child Health and Human Development of the Public Health Service (HD-01247). J. S. is a National Institutes of Health Postdoctoral Fellow (GM-23939).

(2) K. Auwers, *Chem. Ber.*, **22**, 604 (1889).

(3) E. Barrett and A. Lapworth, *J. Chem. Soc.*, **93**, 85 (1908).

(4) B. M. Anderson and W. P. Jencks, *J. Amer. Chem. Soc.*, **82**, 1773 (1960).

(5) W. P. Jencks, *Progr. Phys. Org. Chem.*, **2**, 63 (1964).

(6) A. Williams and M. L. Bender, *J. Amer. Chem. Soc.*, **88**, 2508 (1966).