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Studies on the Reaction Mechanisms in Heterocyclic Compounds. IV.[1] Ionic Mechanism in the Reaction of Benzoyl Peroxide and Substituted Benzaldehyde (2-Phenyl-3-quinoxalinyl)hydrazone

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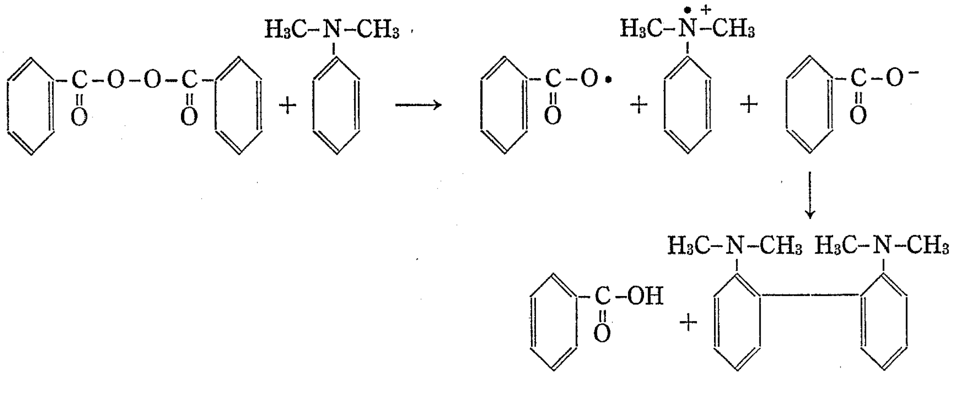
The reaction between benzoyl peroxide and hydrazones follows second-order kinetics, first-order in respect to peroxide and hydrazone. The reaction is accelerated by electron donation groups in hydrazone, and the electronic effect follows Brown-Okamoto's $\rho\sigma^{+}$ relationship. Radical inhibitors and polymerizable monomers have no effect. It was concluded that the reaction is not a radical chain process, but involves an ionic process without radical formation, and a possible reaction mechanism is proposed.

Decomposition of benzoyl peroxide is being studied by the radical reaction mechanism with progress in polymer chemistry. Nozaki and Bartlett[3] examined the decomposition of benzoyl peroxide in various solvents and explained it as a radical decomposition. However, since this decomposition occurs explosively in amines such as aniline and triethylamine, this reaction is not necessarily a decomposition accompanied by the formation of a free radical. Later, Horner and others[4] studied the reaction of benzoyl peroxide and dimethylaniline in detail and stated that it is a reaction accompanied by both ionic and radical reactions.



Imoto and Choe[5] then examined this reaction kinetically. They thought that the lone-pair electrons of the nitrogen in dimethylaniline attacked the $-\overset{\delta^{+}}{\overset{\frown}{\text{O}-\text{O}}}-$ group in benzoyl peroxide to form an ionic addition product, a part of which underwent ionic decomposition and the other a radical decomposition to give the final product. Walling and Hodgdon[6] noted the ionic nature of benzoyl peroxide and examined the reaction of phenol and benzoyl peroxide

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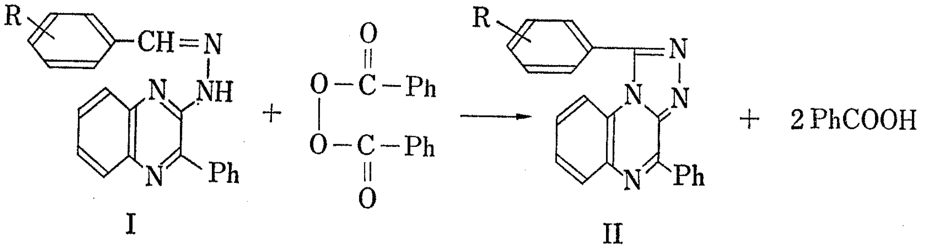
[1] Part III: S. Tagami, K. Sasayama and D. Shiho, *Chem. Pharm. Bnll.* (Tokyo), **17**, 5 (1969).
[2] Location: *Gofuku, Toyama.*
[3] K. Nozaki and P.D. Bartlett, *J. Am. Chem. Soc.*, **68**, 1686 (1946); **69**, 2299 (1947).
[4] L. Horner and K. Scherf, *Ann.*, **573**, 35 (1951); L. Horner and E. Schwenk, *ibid.*, **506**, 69 (1950).
[5] M. Imoto and S. Choe, *J. Polymer Sci.*, **15**, 485 (1955).
[6] C. Walling and R.B. Hodgdon, Jr., *J. Am. Chem. Soc.*, **80**, 228 (1958).

and stated that they could not obtain any evidence of radical reaction and explained this as a pure ionic reaction.

The present writers were interested in the ionic reactivity of benzoyl peroxide and examined the reaction of benzoyl peroxide with benzaldehyde (2-phenyl-3-quinoxalinyl) hydrazone (I), the results of which made it possible to explain this reaction by an ionic mechanism.



Results

Identification of Products

A calculated amount of benzoyl peroxide was added to the benzene solution of the hydrazone (I), the mixture was boiled for 1 hr, and examination of the reaction products showed the formation of *s*-triazolo-quinoxaline (II) and benzoic acid.

Kinetics

The hydrazone (I) was reacted with benzoyl peroxide in benzene solution at a definite temperature and the reaction rate was calculated from the determination of unreacted benzoyl peroxide by iodometry.

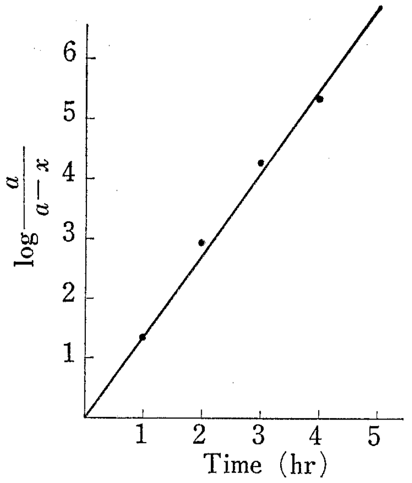


Fig. 1. Reaction of 0.001M Benzoyl Peroxide with 0.05M Benzaldehyde (3-phenyl-2-quinoxalinyl) hydrazone in Benzene at 30°

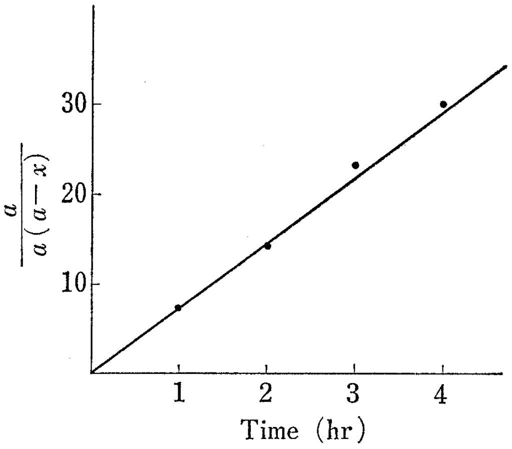


Fig. 2. Reaction of 0.025M Benzoyl Peroxide with 0.025M Benzaldehyde (3-phenyl-2-quinoxalinyl)hydrazone in Benzene at 30°

The reaction of benzoyl peroxide in a concentration of 1.0×10^{-3}M with 50 volumes of the hydrazone (I) at 30° showed this to be a pseudo-first order reaction, as shown in Fig. 1. The same reaction carried out with the concentration of benzoyl peroxide and the hydrazone at 2.5×10^{-2}M showed this to be a second-order reaction, as shown in Fig. 2. Consequently, this reaction rate will be expressed by the following equation.

$$\frac{-d(\text{peroxide})}{dt}=k_2[\text{peroxide}][\text{hydrazone}]$$

Examination of the substituent effect by varying the substituent, R, in the hydrazone in the reactions carried out under identical conditions gave the second-order rate constants, as listed in Table I. When the substituent R is an electron-releasing group like CH_3O, the reaction rate becomes extremely rapid, the rate becoming about 17 times faster than when there is an electron-attracting group like NO_2. Relationship between the log k so obtained and Hammett's σ is plotted in Fig. 3. Substituents with a large -T effect, like p-CH_3O and p-C_2H_5O, deviate largely from the straight line but it was found that the use of the σ^+ value of Brown and Okamoto resulted in all the substituents clustered on the straight line, as shown in Fig. 4.

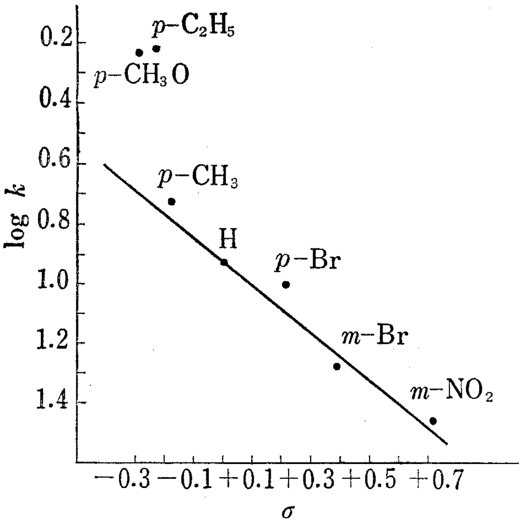


Fig. 3. Hammett's σ Constants and Rate Plots for the Reaction of Benzoyl Peroxide with Substituted(3-phenyl-2-quinoxalinyl) hydrazone

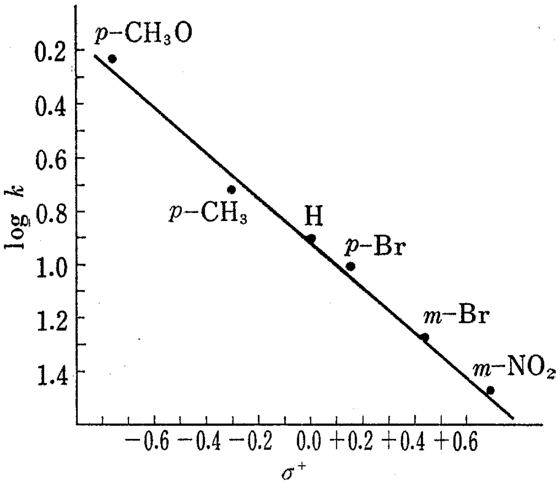


Fig. 4. Brown-Okamoto's σ^+ Constants and Rate Plots for the Reaction of Benzoyl Peroxide with Substituted Benzaldehyde (3-phenyl-2-quinoxalinyl)hydrazone

Radical Traps

If the reaction of benzoyl peroxide and the hydrazone were a radical reaction, the reaction rate should change in the presence of a radical inhibitor. The reaction was therefore examined by the use of various nitrobenzenes$^{7)}$ and sulfur as the radical inhibitor. Reaction of the peroxide in benzene solution with the concentration of the hydrazone at 2.5×10^{-2}M and that of the inhibitor at 2.5×10^{-2}M gave the results shown in Table II. The initial concentration of benzoyl peroxide is indicated as that given in the table at zero hr. Concentration of the remaining peroxide after 3 hr was measured with or without the addition of an inhibitor, and it was found that the concentration was hardly different in these two cases. This fact indicates that the reaction rate does not change whether the inhibitor is added or not.

Table I. Rates of Reaction of 0.025M Benzoyl Peroxide with 0.025M Substituted Benzaldehyde (3-phenyl-2-quinoxalinyl)hydrazone in Benzene at 30°

Substituent	$k_2 \times 10^2$ (moles/liter·min)	Substituent	$k_2 \times 10^2$ (moles/liter·min)
p-CH_3O	59.7	p-Br	11.1
p-C_2H_5O	60.2	m-Br	5.11
p-CH_3	18.6	m-NO_2	3.45
H	12.1		

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7) C. Walling, "Free Radicals in Solution," John Wiley & Sons, Inc., New York, 1957, p. 174.

Table II. Effect of Radical Inhibitors on the Reaction of Benzoyl Peroxide with Hydrazone in Benzene at 30°

Inhibitor,	Concn. (M)	Concn. of benzoyl peroxide ($\times 10^2$M) 0 hr	3 hr
Nitrobenzene	none	2.60	1.81
	0.025	2.60	1.79
o-Dinitrobenzene	none	2.59	1.70
	0.025	2.59	1.73
m-Dinitrobenzene	none	2.58	1.72
	0.025	2.58	1.72
p-Dinitrobenzene	none	2.60	1.82
	0.025	2.60	1.81
Sulfur	none	2.59	1.77
	0.025	2.59	1.72

The same reaction was then carried out with the addition of a polymerizable substance like styrene, methacrylate, and vinyl acetate. If a radical were formed in this reaction, a polymer of these substances should be produced. As shown in Table III, 0.094 g of a polymer was obtained in the reaction of benzoyl peroxide with styrene in benzene solution, at 30° for 75 hr, but the presence of the hydrazone reduced the amount of the polymer to mere 0.001 g. In the reaction with methyl methacrylate or vinyl acetate, at 60° for 4 or 6 hr, respective polymers were obtained in 0.111 g and 0.168 g in the absence of the hydrazone but none in its presence. These experiments produced no evidence that the reaction of benzoyl peroxide and the hydrazone is of radical mechanism.

Table III. Effect of Polymeriable Monomers

Sample in benzene	Concn. (M)	Time (hr)	Temp. (°C)	Polymer formed (g)
Benzoyl peroxide	0.025	75	30	0.094
Styrene	2.00			
Benzoyl peroxide	0.025	75	30	0.001
Hydrazone	0.025			
Styrene	2.00			
Benzoyl peroxide	0.025	4	60	0.111
Methyl methacrylate	1.00			
Benzoyl peroxide	0.025	4	60	0.000
Hydrazone	0.025			
Methyl methacrylate	1.00			
Benzoyl peroxide	0.025	6	60	0.168
Vinyl acetate	1.00			
Benzoyl peroxide	0.025	6	60	0.000
Hydrazone	0.025			
Vinyl acetate	1.00			

Discussion

Experimental results obtained in the reaction of benzoyl peroxide and the hydrazone may be summarized as follows:

1) The reaction follows the second–order mechanism, but is a first–order with respect to the hydrazone and benzoyl peroxide.

2) The reaction rate is increased when the substituent in the hydrazone is an electron–donating group.

3) The electronic effect does not follow Hammett's correlation formula but does that of Brown–Okamoto's formula.

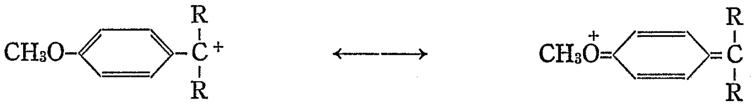
4) Use of a radical inhibitor like sulfur and nitrobenzenes failed to bring about any change in the reaction rate.

5) Addition of a monomer like styrene, methyl methacrylate, or vinyl acetate failed to produce their polymer.

These results give no evidence that this is a radical reaction. The first item summarized in (1) indicates that the reaction of benzoyl peroxide and dimethylaniline proceeds by both ionic and radical reactions so that the reaction follows the second–order mechanism in the initial step and, as the reaction progresses, the radical is induced, and it is no longer a second–order reaction. In contrast, the reaction of benzoyl peroxide and the hydrazone is a second–order reaction even when the reaction has progressed 65% and this fact seems to suggest that there has been no induction of a radical during this reaction.

The last two items in the above summarization seem to us compelling evidence against any radical chain mechanism for the peroxide-hydrazone reaction since radical traps are effective in repressing other peroxide chain decompositions.[3,8,9] Consequently, this reaction should be considered to follow an ionic mechanism. The item in (2) above indicates that the lone–pair electrons of the nitrogen has attacked oxygen of the peroxide, as in the reaction of dimethylaniline and benzoyl peroxide.[4,5] For this reason, an electron–donating substituent would increase the electron density of the nitrogen and accelerate the reaction. In the case of the hydrazone, however, there are secondary and tertiary nitrogens, and which lone–pair electrons attack the oxygen in benzoyl peroxide is still not clear. The item given under (3) offers valuable evidence for solving this point.

In Hammett's equation log $k/k_0=\rho\sigma$, the substitution constant, σ, is expressed as the sum of inductive effect, σ_I, and polar resonance effect, σ_R, *i.e.* $\sigma=\sigma_I+\sigma_R$.[10] Hammett's σ_R shows the size of increase or decrease in electron density, obtained as a result of resonance between a benzene ring and a substituent, that is transmitted to the reaction center by a polar mechanism. In electrophilic reactions, resonance between a substituent and a reaction center would prohibit the reaction to follow Hammett's equation when the substituent has a large -T effect like CH_3O.



Brown-Okamoto's σ^+[10,11] was obtained by correction of such an additive resonance item.

$$\sigma^+=\sigma_I+\sigma_R+\Delta\sigma_R f'(\rho)$$

The reaction of benzoyl peroxide and the hydrazone follows the Brown–Okamoto's equation, as indicated in Fig. 4. This fact suggests that there is a resonance between the reaction center and the substituent. Taking this fact into consideration, it seems more likely that the lone-pair electrons of =N– rather than those of –NH– attack the oxygen in benzoyl peroxide.

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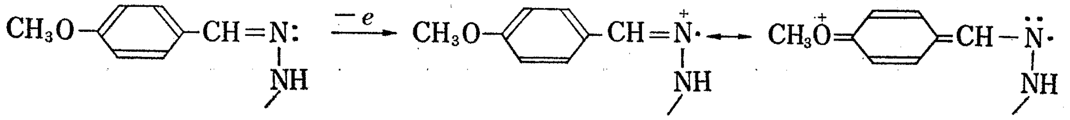
[8] C.G. Swain, W. Stockmeyer and T. Clarke, Jr., *J. Am. Chem. Soc.*, **72**, 5426 (1950).

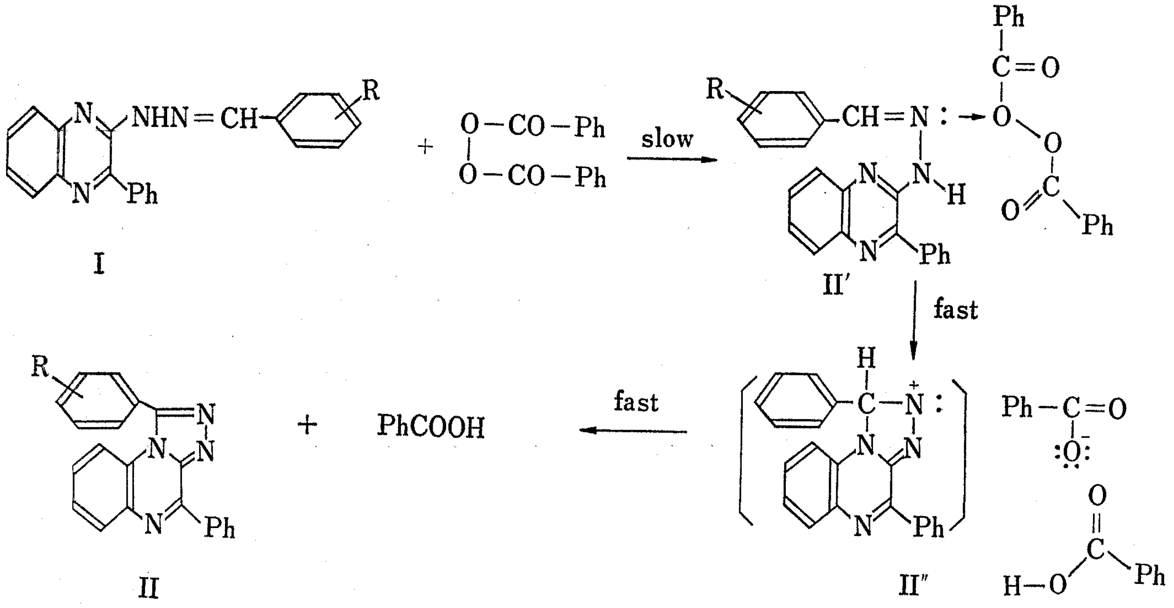
[9] G.S. Hammond, *J. Am. Chem. Soc.*, **72**, 3737 (1950); G.S. Hammond and L.M. Soffer, *ibid.*, **72**, 4711 (1950).

[10] Y. Yukawa and Y. Tsuno, *Bull. Chem. Soc. Japan*, **32**, 960 (1959).

[11] H.C. Brown and Y. Okamoto, *J. Am. Chem. Soc.*, **79**, 1913 (1957); *J. Org. Chem.*, **22**, 485 (1957).



Based on these results, the following mechanism is proposed for the reaction of benzoyl peroxide and the hydrazone.



Since this reaction follows the second–order mechanism, the step of formation of the addition product (II′) would be the rate–determining step. This fact suggests that, as in the reaction of benzoyl peroxide and dimethylaniline reported by Imoto and others,[5] the reaction of the peroxide and the hydrazone also progresses by the following equation.

$$\frac{-d(\text{peroxide})}{dt}=k_2[\text{peroxide}][\text{hydrazone}] \qquad (1)$$

The peroxide molecule reacts with one mole of the hydrazone to undergo decomposition, and this reaction can be expressed by the following equations.

$$\text{peroxide}+\text{hydrazone} \underset{k_b}{\overset{k_a}{\rightleftharpoons}} [\text{peroxide–hydrazone}] \qquad (2)$$

$$[\text{peroxide–hydrazone}] \xrightarrow{k_c} \text{decomposition products} \qquad (3)$$

In these equations, [peroxide–hydrazone] indicates the addition product (II′). If it is taken for granted that a stationary state exists, the following equation will be established.

$$\frac{d[\text{peroxide–hydrazone}]}{dt}=k_a[\text{peroxide}][\text{hydrazone}] \\ -(k_b+k_c)[\text{peroxide-hydrazone}]=0$$

therefore,

$$[\text{peroxide–hydrazone}]=\frac{k_a}{k_b+k_c}[\text{peroxide}][\text{hydrazone}]$$

Since the decomposition of the peroxide occurs through the reaction of (2),

$$-\frac{d[\text{peroxide}]}{dt}=k_c[\text{peroxide–hydrazone}]$$

$$=\frac{k_a k_c}{k_b+k_c}[\text{peroxide}][\text{hydrazone}] \qquad (4)$$

Equation (4) is none other than equation (1) obtained experimentally and k_2 in equation (1) is essentially expressed by the following equation.

$$k_2=\frac{k_a k_c}{k_b+k_c} \qquad (5)$$

If the value of k_a is far larger than that of k_b, then

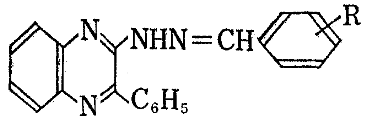
$$k_2 \fallingdotseq k_a$$

Therefore, k_2 is determined at the step of adduct formation, k_a, and this is the rate-determining step.

Experimental

Materials——Benzoyl peroxide employed was purified by dissolving about 25 g in 330 ml of acetone at room temperature, precipitating by the addition of 700 ml of distilled water with stirring, filtering, and thoroughly drying the product in air stream. Hydrazones listed in Table IV were recrystallized from EtOH. Benzene used for the rate studies was purified by treatment with H_2SO_4 in the usual manner.

TABLE IV. Hydrazone



R	mp (°C)	R	mp (°C)
H	128	*m*-Br	135
m-NO_2	175	*p*-Br	187
p-OCH_3	164	*p*-CH_3	114
p-OC_2H_5	156		

Rate Studies——A test tube of about 8 ml capacity was cleaned with H_2SO_4–dichromate. The hydrazone dissolved in benzene was placed in this test tube and the solution kept at 30°. To this was added a solution of benzoyl peroxide in benzene kept at the same temperature. The total volume was adjusted exactly to 6 ml. In each experiment, 8—9 test tubes equipped with a ground-glass stopper were employed. Before closing, air was displaced by flushing with nitrogen. The tubes were placed in a well-stirred thermostat at 30° or at other temperature.

Peroxide Analysis——The procedure used was that of Cass[12] with minor modifications. The sample was pipetted into the reaction mixture which consisted of 20 ml of glacial AcOH, 1 ml of freshly prepared saturated KI solution. After 5 min, 10 ml of H_2O was added and the mixture was titrated with 0.05 N $Na_2S_2O_3$ solution. Starch solution was used as the indicator.

Polymerization Experiments——The experiments listed in Table III were carried out in nitrogen. A 6 ml sample was added to 100 ml of MeOH. The precipitated polymer was collected by filtration and dried.

Acknowledgement We are gratefull to Miss M. Hotta and Miss Y. Hotta for their technical assistance.

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[12] W.E. Cass, *J. Am. Chem. Soc.*, **68**, 1976 (1946).