halogen-free product was practically insoluble in ether or benzene. Mineral acids also failed to dissolve it, but it gave a reddish-colored solution with 5% potassium hydroxide.

Anal. Calcd. for $C_6H_6N_2O_3S$: N, 15.05. Found: N, 15.06.

N-(3-Nitro-5-acetyl-2-thienyl)-aniline.—To a warm solution of 0.2 g. of 4-nitro-5-chloro-2-acetothienone in 10 ml. of methanol was added 1 g. of aniline. Within a few minutes a mass of crystals formed (0.2 g.). Recrystallization from methanol gave orange needles, m.p. 138.5–139.5°, free from halogen.

Anal. Calcd. for $C_{12}H_{10}N_2O_3S$: N, 10.68. Found: N, 11.11.

N-(3-Nitro-5-acetyl-2-thienyl)-butylamine.—The above procedure was repeated using butylamine in place of aniline. No solid product separated after 30 minutes. Acidification and dilution with water gave a yellow solid, very soluble in methanol. Recrystallization from hexane yielded fine yellow needles, m.p. 96.5–97.5°, which contained no halogen.

Anal. Calcd. for $C_{10}H_{14}N_2O_3S$: N, 11.56. Found: N, 11.46.

EVANSTON, ILLINOIS

[COMMUNICATION NO. 1455 FROM THE KODAK RESEARCH LABORATORIES]

The Reaction of Quinone and Sulfite. I. Intermediates[1]

BY JAMES E. LUVALLE

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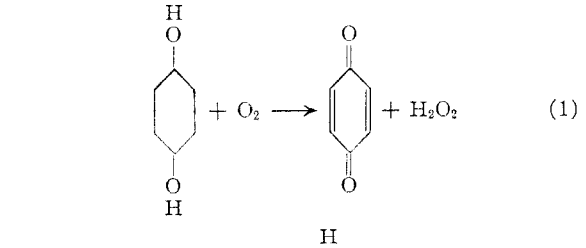
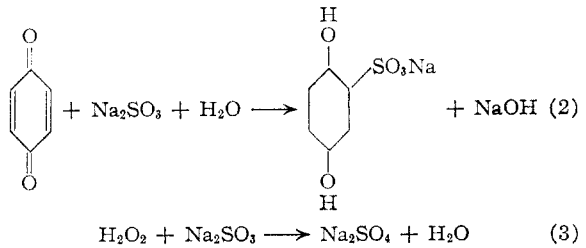
The reactions of quinone and sulfite, quinhydrone and sulfite, and quinone monosulfonate and sulfite have been investigated over the *p*H range 1 to 12. Below *p*H 4 the products of the reaction between quinone and sulfite or quinhydrone and sulfite are hydroquinone, sulfate and hydroquinone monosulfonate; between *p*H 4 and 7.5 the product is hydroquinone monosulfonate. Below *p*H 8.5 the quinhydrone acts as though only quinone were present. Above *p*H 7.5 a greenish-blue intermediate appears in the reaction of quinone and sulfite; this intermediate increases in stability with increase in *p*H, whereas above this *p*H the greenish-blue intermediate does not appear in the reaction of quinhydrone and sulfite. Over the whole *p*H range in the reaction of quinone and sulfite, a transient orange intermediate is apparently the first step in the reaction. The reaction of quinone monosulfonate and sulfite parallels the reaction of quinone and sulfite in part, *i.e.*, at low *p*H values the reaction is a simple oxidation–reduction reaction, between *p*H 2.7 and 7.0 it goes through a transition range, and above *p*H 7 the product is virtually all quinone disulfonate. In the transition range a yellow intermediate, probably a semiquinone, appears. Quinone also forms a greenish-blue intermediate with cysteine and glutathione and a very transient greenish complex with *l*-ascorbic acid. The greenish-blue intermediates bleach in the light and are regenerated by shaking in air.

Introduction

The reaction of quinone and sulfite is the first of a series of some very rapid reactions of photographic interest which are now being studied in these Laboratories. Although the use of sulfite as a preservative in photographic developers was first mentioned in 1882,[2] the mechanism of the sulfite action has not been adequately explained. The data for the autoxidation of hydroquinone in an alkaline medium and in the presence of excess sulfite have been explained by the reaction scheme[3]



(1)



(2)

$$H_2O_2 + Na_2SO_3 \longrightarrow Na_2SO_4 + H_2O \qquad (3)$$

It was reasoned by analogy that quinone was formed in the developing solution, and thence removed by the sulfite, with formation of hydroquinone monosulfonate.

When quinone and sulfite react in air[4a–4c] or under hydrogen[4b] in an alkaline medium, an unstable green (or greenish-blue) compound is formed which, upon standing, fades to bright yellow[4a,c] or red brown.[4b] Shaking in air restores the color.[4a–4c] A trace of bisulfite or hydroquinone, added before the sodium sulfite, is reported[4a] to prevent formation of the colored intermediate. Hydroquinone monosulfonate is also found,[4b,c] and reduction of the alkalinity increases the yield of the monosulfonate.[4c] The theoretical yield of the monosulfonate is obtained from the reaction in a buffer alcohol–water solution between *p*H 4.5 and 5.0.[4d]

Experimental

All inorganic chemicals were General Chemical Reagent Grade. Ordinary distilled water was used. Unless otherwise stated, *p*H measurements were made with a Beckman Model G laboratory *p*H meter. The visual spectra were recorded on a General Electric Recording Spectrophotometer and the ultraviolet spectra with a Beckman Model DU spectrophotometer. On recording the visual spectra, the wave length drive was driven manually to permit recording of a complete curve in one minute. The solutions were prepared by discharging from hypodermic syringes, sulfite always preceding quinone, into a beaker containing an aliquot of buffer. The reaction mixture was immediately transferred to a cuvette and placed in the spectrophotometer, elapsed time from mixing to start of recording being not more than 30 seconds. Two absorption curves were recorded consecutively, the cuvette was removed, the solution

(1) Presented before the Division of Biological Chemistry at the Philadelphia Meeting of the American Chemical Society, April, 1950.

(2) H. B. Berkely, *Phot. News*, **26**, 41 (1882).

(3) (a) J. Pinnow, *Z. wiss. Phot.*, **11**, 289 (1913); *ibid.*, **13**, 44 (1914); *ibid.*, **27**, 344 (1930); *ibid.*, **37**, 76 (1938); (b) E. Lehmann and E. Tausch, *Phot. Korr.*, **71**, 17 (1935); (c) T. H. James and A. Weissberger, THIS JOURNAL, **61**, 442 (1939).

(4) (a) R. Luther and A. J. Leubner, *J. prakt. Chem.*, **85**, 233 (1912); (b) J. Pinnow, *ibid.*, **89**, 536 (1914); (c) J. W. Dodgson, *J. Chem. Soc.*, **105**, 2435 (1914); (d) G. H. Chase, W. T. Hanson, Jr., and R. M. Evans, private communication.

remixed with that remaining in the beaker, an aliquot of concentrated sulfite added, the resulting mixture replaced in the cuvette, and two more consecutive absorption curves were recorded. In some cases, the mixture was held a half-hour and a fifth curve was obtained.

Ultraviolet absorption curves were obtained over as wide a range of *p*H values as possible under air, with no attempt to exclude oxygen. Immediately after the reaction, the product was diluted 25-fold and 250-fold, and ultraviolet absorption curves were rapidly obtained. The concentrations were adjusted so that the maximum density near *p*H 2 was between 1.0 and 1.5.

Hydroquinone and *p*-benzoquinone[5] were specially purified samples of Eastman White Label hydroquinone and *p*-benzoquinone.

Sodium Hydroquinone Monosulfonate.[5]—One hundred grams of technical grade sodium hydroquinone monosulfonate was extracted by 3 l. of methanol, leaving 10 g. of insoluble material. The methanol extract was concentrated to 1500 cc. and chilled. The precipitate (37.2 g.) was dissolved in 1500 cc. of hot methanol, decolorized with Special Filtrol and concentrated to the point of crystallization. The yield was 25.5 g.

Anal. Calcd. for $C_6H_6O_6SNa$: C, 34.0; H, 2.4; S, 15.1. Found: C, 34.0; H, 2.5; S, 14.8.

Further material of lesser purity was obtained by working up the filtrates, but was not used in these experiments.

Potassium Quinone Monosulfonate.[5]—Sodium hydroquinone monosulfonate (7.4 g.) was dissolved in 40 ml. of warm water, cooled to 10°, and 7.5 ml. of concentrated H_2SO_4 was added with stirring. The mixture was cooled to 0° and 14.9 g. of lead dioxide was gradually added with vigorous stirring. The mixture was held at 0° for one hour longer, stirring constantly, then warmed to 45°, stirred for 10 minutes, and filtered. A saturated solution of potassium chloride (17.5 g. in 50 ml. of water) was added to the filtrate. The mixture was allowed to stand in the refrigerator overnight, and the golden brown crystals were collected; yield 6.19 g. (77.5).

Anal. Calcd. for $C_6H_3O_5SK$: C, 31.9; H, 1.3; S, 14.2. Found: C, 31.4; H, 1.3; S, 14.5.

Potassium Hydroquinone Disulfonate.[5]—To a solution of 120 g. of anhydrous K_2SO_3 in 400 ml. of water was added 34.7 g. of potassium quinone monosulfonate, followed by 60 ml. of acetic acid. The mixture was shaken thoroughly and was allowed to stand in the refrigerator over the weekend. The 21.4 g. of crystals obtained was recrystallized from 200 ml. of 1 part of acetic acid and 4 parts of water. The yield was 13.7 g. (25.7%). Digestion with 25 volumes of methanol gave a 96% recovery. The disulfonate is anhydrous, contrary to the findings of earlier work.[4b]

Anal. Calcd. for $C_6H_4O_8S_2K_2$: C, 20.8; H, 1.2; S, 18.5. Found: C, 20.7; H, 1.3; S, 17.9, 18.0

Cysteine.—Eastman White Label Product.

Glutathione.—Eastman White Label Product.

***l*-Ascorbic Acid.**—Eastman White Label Product.

Hydrazine Dihydrochloride.—Eastman White Label Product.

Results and Discussion

The original experiments with quinone and sulfite were undertaken to check the hypothesis that quinone is formed in the developing solution by the reaction of silver halide and developer and subsequently reacts with sulfite to form hydroquinone monosulfonate. It was found that when quinone is added to a buffer at *p*H 10.2 containing a large excess of sulfite, a series of transient colors is formed yielding finally a stable orange solution. Since it was possible that the colors were due to large local excesses of quinone, a saturated solution of quinone was prepared in hexane and in chloroform, respectively, the yellow solutions decanted from the undissolved quinone and each mixed with an aliquot of *p*H 10.2 buffer containing 0.3 *M* sulfite. In each case an instantaneous transfer of color to the water layer took place, giving an orange-red solution (hexane solution + buffer) and a dark red-brown solution (chloroform solution + buffer).

To facilitate observation of the transient colors, the mixing unit of the flow machine[6] was used. A quinone solution was placed in one arm of the unit and a sulfite solution buffered at *p*H 10 in the other arm. When the solutions were mixed, an extremely transitory orange-pink color preceded the formation of a greenish-blue solution, which slowly (in the course of a few minutes) changed to an orange-yellow solution. Between *p*H 4.5 and 7 the reaction of quinone and sulfite yielded a colorless solution. When a weakly buffered solution of sulfite at *p*H 10 was mixed with quinone in the mixing unit and thence flowed directly into a strongly buffered solution at *p*H 4 or 7, the green solution became colorless when it entered the *p*H 4.0 solution or faint golden when it entered the *p*H 7.0 solution. That is, the greenish-blue solution yielded a colorless product if acidified soon after formation. When a strongly buffered *p*H 10 solution without sulfite was mixed with quinone, the initial color of the mixture was always yellow, followed by a slow darkening to a deep red; therefore, quinone alone at *p*H 10 does not yield the transients found in the reaction of quinone and sulfite at *p*H 10.

Three solutions were prepared at *p*H 10.63 with a sulfite quinone ratio of unity and allowed to stand 40 minutes; one in the light, one in the light over fresh silver bromide, and one in the dark. The solution in the light faded and was regenerated several times by shaking in the air during this period; regeneration, however, was never complete, the originally clear solution becoming murkier with each regeneration. The solution standing in the light over the silver bromide became a darker green but did not fade, while the solution standing in the dark remained greenish-blue but developed a slight murkiness. The sensitivity to light and oxygen (or silver halide as oxidizing agent) suggests that the greenish-blue substance may be a free radical. When a solution of the greenish-blue substance was faded in the light and was then placed in the dark, it was partially regenerated.

Experiments showed that the stability of the greenish-blue substance increases with *p*H (Fig. 1) and has a maximum value when the sulfite–quinone ratio is unity. Transmission or density curves were obtained for the product of the sulfite–quinone reaction from *p*H 1 to 12. Figure 2 gives the variation of optical density with *p*H at 400 and 610 mμ with solutions 90 seconds old. The greenish-blue substance has an appreciable, stable density at 610 mμ above *p*H 9.2. It may be detected by the eye as a transient color somewhat below *p*H 9.0. The small hump in the D_{400} curve between *p*H 6.5 and 8 may be due to the end product from the transient orange-pink compound that appears initially above *p*H 2. Figure 3 gives the variation in stability of the greenish-blue substance with *p*H; the stability increases rapidly above *p*H 9.0. Stability is given as the ratio of density at 610 mμ of solutions 90 seconds old to those 30 seconds old. The greenish-blue compound is formed in phosphate, pyrophos-

(5) J. R. Thirtle and R. L. Bent prepared these reagents.

(6) Description to be published.

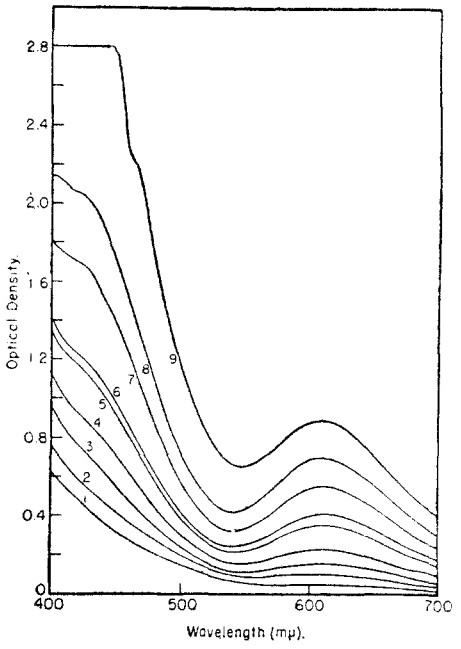


Fig. 1.—Density curves for the greenish-blue intermediate at several values of *p*H in carbonate buffer. Sulfite–quinone ratio is unity: curve 1, *p*H 9.72; curve 2, *p*H 9.99; curve 3, *p*H 10.18; curve 4, *p*H 10.32; curve 5, *p*H 10.43; curve 6, *p*H 10.54; curve 7, *p*H 10.72; curve 8, *p*H 10.90; curve 9, *p*H 11.20.

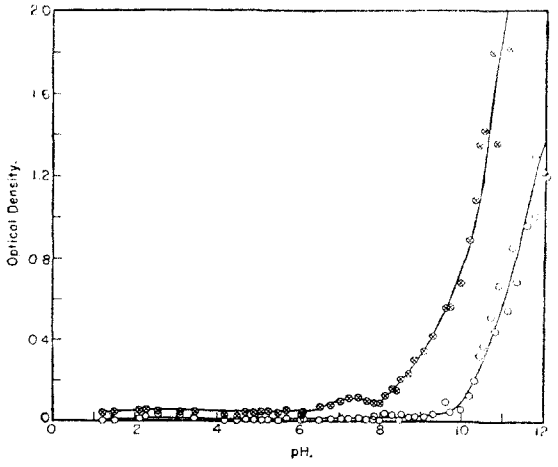


Fig. 2.—Variation in optical density of the sulfite–quinone reaction product, at 400 and 610 mμ, with *p*H: O, D_{610}; ⊗, D_{400}.

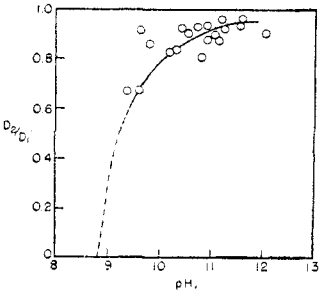


Fig. 3.—Variation in stability of the greenish-blue intermediate with *p*H.

phate, sodium *p*-phenolsulfonate, carbonate and diethylglycine buffers; hence it appears to be independent of the nature of the buffering salt. Comparison of the dissociation curves for sulfurous acid and hydroquinone with Fig. 2 shows that there is no relation between the ionization of these substances and the appearance of the greenish-blue intermediate.

Bleaching of the greenish-blue substance by light was accelerated to some extent by *l*-ascorbic acid, hydrazine, hydroquinone, or an excess of sulfite. Persulfate in very small amounts regenerated the greenish-blue substance; however, when larger amounts of persulfate were used, the greenish-blue compound was not only regenerated but also destroyed. Table I shows that the fading of the greenish-blue compound is accompanied by a decrease in *p*H, this decrease increasing as the buffer capacity of the solution is lowered. Therefore, hydroxyl ion is used up in the fading reaction and released in the regeneration reaction.

TABLE I

CHANGE IN *p*H AS GREENISH-BLUE SOLUTION BLEACHES

Buffer, *M*	Greenish-blue compound Initial *p*H	Partially faded *p*H	Color re-generated *p*H	Faded *p*H	Δ *p*H
0.25	10.49	10.48	10.48	10.44	−0.05
.10	10.45	10.30	10.35	10.32	− .13
.04	10.29	10.22	...	10.12	− .17
	10.16	10.02	10.10	9.92	− .24

Table II shows that the greenish-blue substance does not obey Beer's law. As the dilution increases, a positive deviation from Beer's law also increases; this indicates that the greenish-blue substance is not a dimer, inasmuch as the deviation should then be negative.

TABLE II

BEER'S LAW AND THE GREENISH-BLUE COMPOUND

Buffer, ml.	0.04 *M* Quinone, ml.	0.05 *M* Sulfite, ml.	H_2O, ml.	Total volume, ml.	Observed *D*	Calcd. (Beer's law), *D*	Deviation, %
20	10	10	4	44	0.603	(0.603)	..
20	4	4	12	40	.364	.266	+37
20	2	2	16	40	.184	.133	+38
20	1	1	18	40	.111	.067	+51
24	8	8	...	40	.561	(.561)	..
24	8	8	40	80	.318	.280	+14
24	8	8	120	160	.224	.140	+60
24	8	8	280	320	.130	.070	+86

Quinone can be formed by oxidation of hydroquinone. Quinhydrone may be considered as 50% quinone, 50% hydroquinone. Hydroquinone monosulfonate is the reaction product when hydroquinone is oxidized in the presence of sulfite. It was then of interest to find out what happened when sulfite was added to solutions of hydroquinone, quinhydrone and hydroquinone monosulfonate (1) after autoxidation had started, and (2) prior to autoxidation. Therefore, solutions of hydroquinone, quinhydrone and hydroquinone monosulfonate were mixed with aliquots of *p*H 12.3 buffer. Autoxidation commenced immediately, the solutions very rapidly turned yellow and commenced to darken. Rapid addition of aliquots of potassium sulfite to these yellow solutions caused the hydroquinone and quinhydrone solutions to become greenish-blue, while

the hydroquinone monosulfonate solution became colorless. When the sulfite was added to the buffer prior to the addition of the developer, the hydroquinone and hydroquinone monosulfonate solutions remained colorless for some time, while the quinhydrone solution instantly turned golden and slowly darkened. When hydroquinone monosulfonate or the golden product of the reaction of quinhydrone and sulfite was placed in a solution with quinone and high *p*H buffered sulfite added, the greenish-blue compound was formed. Figure 4 gives the absorption curves for the product of the reaction of quinone and sulfite, and of quinhydrone and sulfite at *p*H 12.2. In the reaction of quinone and sulfite, the transient orange-pink color appeared near *p*H 2, the depth of color increased to *p*H 9 and then appeared to lessen, but it always preceded the formation of the greenish-blue color. Quinhydrone and sulfite, or quinone monosulfonate and sulfite did not form a green or greenish-blue substance at any value of *p*H between 1 and 12.

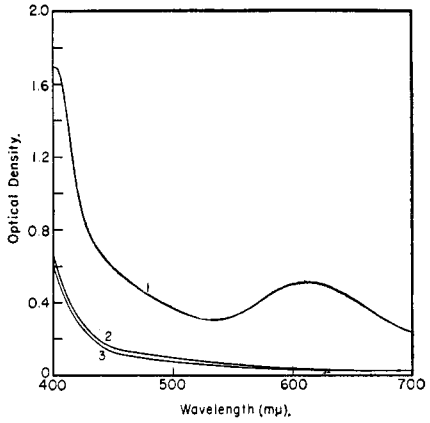


Fig. 4.—Greenish-blue intermediate in *p*H 12.2 phosphate buffer: curve 1, quinone and large excess of sulfite; curve 2, Eastman Kodak quinhydrone and large excess of sulfite; curve 3, freshly prepared quinhydrone and large excess of sulfite. The quinhydrone does not yield a greenish-blue intermediate.

Some information as to the location of the bond between quinone and sulfite in the greenish-blue compound was desired. It was also of some interest to determine if other compounds would give the greenish-blue intermediate with quinone. Solutions of sulfite were treated with quinone, quinone monosulfonate, quinhydrone, toluquinone, 2,5-xyloquinone and duroquinone in *p*H 12.2 buffer. Solutions of glutathione and cysteine were treated with quinone, toluquinone, 2,5-xyloquinone and duroquinone. Solutions of *l*-ascorbic acid and hydrazine were treated with quinone, all in buffer at *p*H 12.2. The data are summarized in Table III. It is observed that increasing methylation of the ring sterically hinders the reaction of sulfite and the sulfhydryl compounds with the quinones. The sulfur-containing compounds gave a much more stable greenish-blue compound with quinone than did *l*-ascorbic acid. The oxidation of hydroquinone in the presence of sulfite did not yield the greenish-blue compound. Figure 5 shows the absorption curves for the compound formed between

TABLE III

REACTION OF SUBSTITUTED BENZOQUINONES, HYDROQUINONE, AND QUINHYDRONE WITH SULFITE, GLUTHATHIONE, CYSTEINE, *l*-ASCORBIC ACID AND HYDRAZINE BUFFER *p*H 12.22

	Sulfite	Glutathione	Cysteine	*l*-Ascorbic acid	Hydrazine
Benzoquinone	Greenish-blue	Greenish-blue	Green	Transient greenish-blue, then colorless	Pink
Toluquinone	Greenish-blue	Greenish-blue	Green		
2,5-Xyloquinone	Yellow	Yellow	Green		
Duroquinone	Yellow	Yellow	Yellow		
Quinone monosulfonate	Colorless				
Hydroquinone autoxidized in presence of sulfite	Colorless				
Hydroquinone oxidized by AgBr in presence of sulfite	Colorless				
Quinhydrone	Golden				

quinone and the sulfhydryl substances, cysteine and glutathione. It is observed that the 1:1 compounds give the maximum absorption.

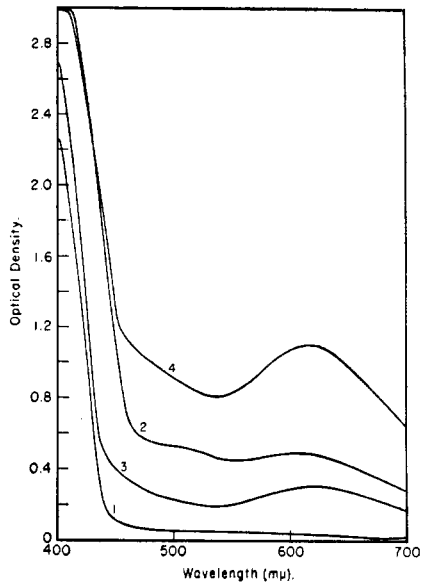


Fig. 5.—Intermediates resulting from reaction of sulfhydryl compounds and quinone in *p*H 12.2 phosphate buffer: curve 1, 5-fold excess of cysteine; curve 2, 1:1 compound of cysteine and sulfite: curve 3, 5-fold excess of glutathione; curve 4, 1:1 compound of glutathione and quinone.

Transmission curves of quinone and quinhydrone were obtained. The data are summarized in Table IV. The wave length of maximum absorption, and

TABLE IV

EFFECT OF *p*H ON QUINONE AND QUINHYDRONE

Substance	Concn. *M*	*p*H	λ_{max} mμ	Density	
Quinone	0.010	2.0	424	0.20	424 mμ
		4.0	424	.19	
		6.0	424	.20	
		8.4	Below 400	.43	
Quinhydrone	.010	2.0	420 (shoulder)	0.27	420 mμ
		4.0	420 (shoulder)	.26	
		6.0	420 (shoulder)	.27	
		8.4	Below 400	.51	

the optical density are identical for quinone at *p*H 2, 4 and 6, and for quinhydrone at *p*H 2, 4 and 6. In both cases, however, the wave length of maximum absorption shifted to below 400 mμ at *p*H 8.4, and the optical density increased. This change in absorption may or may not be of importance in the reaction of quinone and sulfite.

Results

Spectrophotometric; 200–400 mμ; Yield Data. —Ultraviolet absorption curves were obtained for hydroquinone, hydroquinone monosulfonate, hydroquinone disulfonate, quinone and quinone monosulfonate. The molal absorbancies were calculated for hydroquinone, hydroquinone monosulfonate and hydroquinone disulfonate. Figure 6 gives the variation in optical density with *p*H for 4.00×10^{-4} *M* solutions of hydroquinone at 288.5 mμ, of hydroquinone monosulfonate at 300.5 mμ, and of hydroquinone disulfonate at 313 mμ. The variation in optical density for the latter two substances at the wave lengths indicated is also given for the presence of a 10-fold excess of sulfite. The discrepancies in the data for hydroquinone monosulfonate and disulfonate in the presence and absence of sulfite at low *p*H are caused by the absorption of either H_2SO_3 or SO_2 (aq). The discrepancies at high values of *p*H are due to the suppression of autoxidation by the sulfite. The data for hydroquinone do not extend above *p*H 6.58 because of the high rate of autoxidation at the higher *p*H's. The molal absorbancies decrease in the order, hydroquinone disulfonate, hydroquinone monosulfonate, and hydroquinone, as is evident from the figure.

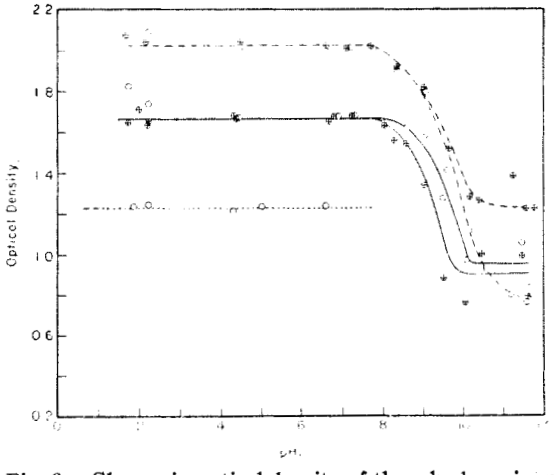


Fig. 6.—Change in optical density of three hydroquinones (4.00×10^{-4} *M*) with *p*H at maximum absorption: O...O, hydroquinone, $D_{288.5}$; ⊕——⊕, hydroquinone monosulfonate, $D_{300.5}$; O——O, hydroquinone monosulfonate in presence of 4.00×10^{-3} *M* sulfite, $D_{300.5}$; ⊕- - -⊕, hydroquinone disulfonate, D_{313}; O- - -O, hydroquinone disulfonate in presence of 4.00×10^{-3} *M* sulfite, D_{313}.

Ultraviolet absorption curves were obtained for the diluted reaction products of the reaction of sulfite with quinone, quinhydrone and quinone monosulfonate, respectively. The sulfite–quinone and sulfite–quinhydrone reactions were run with sulfite dye ratios of 1, 2 and 10, while the sulfite–quinone monosulfonate reaction was run with a sulfite dye ratio of 10. Figures 7, 8 and 9 give selected absorption curves for the products of the reaction of

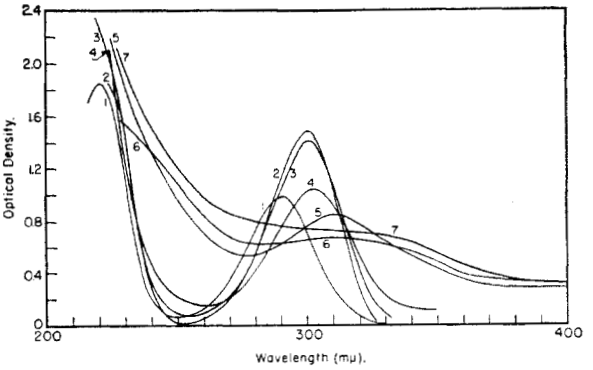


Fig. 7.—Change in ultraviolet absorption of the product of the quinone–sulfite reaction with *p*H 1.00 × 10^{-2} *M* quinone treated with 1.00 × 10^{-2} *M* sulfite and product diluted 25-fold. The *p*H given is that of the diluted solution: curve 1, *p*H 2.04; curve 2, *p*H 4.38; curve 3, *p*H 7.14; curve 4, *p*H 8.42; curve 5, *p*H 9.62; curve 6, *p*H 10.18; curve 7, *p*H 11.05.

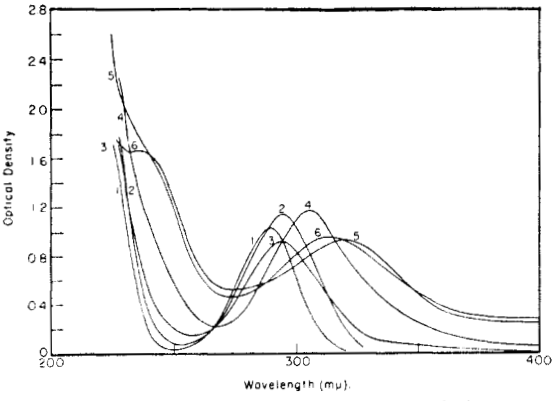


Fig. 8.—Change in ultraviolet absorption of the product of the quinhydrone–sulfite reaction with *p*H. 5.00 × 10^{-3} *M* quinhydrone treated with 1.00 × 10^{-2} *M* sulfite and product diluted 25-fold. The *p*H given is that of the diluted solution: curve 1, *p*H 1.66; curve 2, *p*H 6.72; curve 3, *p*H 8.50; curve 4, *p*H 9.12; curve 5, *p*H 10.08; curve 6, *p*H 10.66.

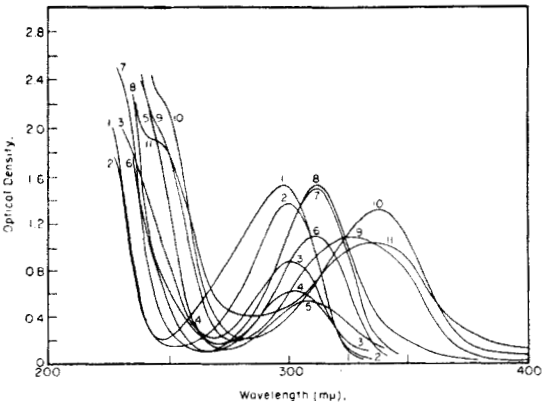


Fig. 9.—Change in ultraviolet absorption of the product of the quinone–monosulfonate–sulfite reaction, with *p*H. 3.6 × 10^{-4} *M* quinone monosulfonate treated with 3.60 × 10^{-3} *M* sulfite: curve 1, *p*H 1.67; curve 2, *p*H 3.90; curve 3, *p*H 4.40; curve 4, *p*H 4.96; curve 5, *p*H 6.02; curve 6, *p*H 7.30; curve 7, *p*H 8.50; curve 8, *p*H 9.71; curve 9, *p*H 10.64; curve 10, *p*H 11.66.

sulfite with quinone, quinhydrone and quinone monosulfonate, respectively. The mole per cent. yields of hydroquinone, hydroquinone monosulfonate and hydroquinone disulfonate for the reactions of quinone, quinhydrone and quinone monosulfonate with sulfite are plotted against *p*H in Figs. 10, 11 and 12, respectively. Table V summarizes the yield data.

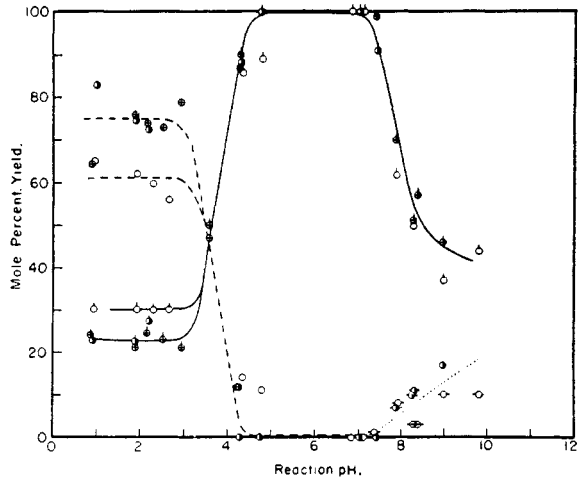


Fig. 10.—Variation of the mole per cent. yield of hydroquinone, hydroquinone monosulfonate and hydroquinone disulfonate with *p*H for the reaction of sulfite and quinone. Hydroquinone: ⊕, sulfite–quinone ratio = 1; ◑, sulfite–quinone ratio = 2; ○, sulfite–quinone ratio = 10. Hydroquinone monosulfonate: ⊕, sulfite–quinone ratio = 1; ◑, sulfite–quinone ratio = 2; ○, sulfite–quinone ratio = 10. Hydroquinone disulfonate: -⊕-, sulfite–quinone ratio = 1; -◑-, sulfite–quinone ratio = 2; -○-, sulfite–quinone ratio = 10.

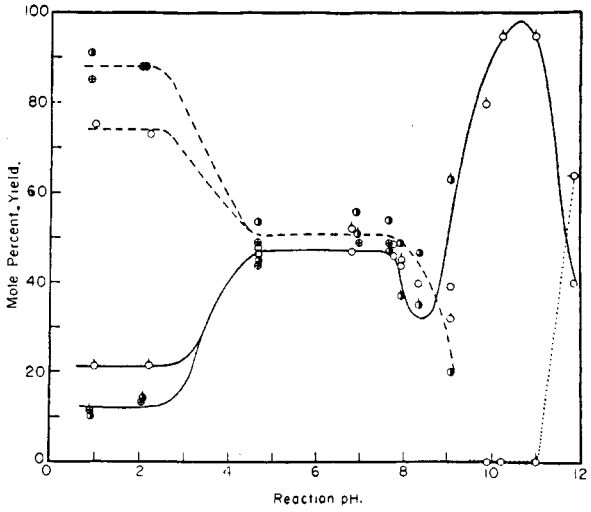


Fig. 11.—Variation of the mole per cent. yield of hydroquinone, hydroquinone monosulfonate, and hydroquinone disulfonate with *p*H for the reaction of sulfite and quinhydrone. Hydroquinone: ⊕, sulfite–quinone ratio = 2; ◑, sulfite–quinone ratio = 4; ○, sulfite–quinone ratio = 20. Hydroquinone monosulfonate: ⊕, sulfite–quinone ratio = 2; ◑, sulfite–quinone ratio = 4; ○, sulfite–quinone ratio = 20. Hydroquinone disulfonate: -⊕-, sulfite–quinone ratio = 2; -◑-, sulfite–quinone ratio = 4; -○-, sulfite–quinone ratio = 20.

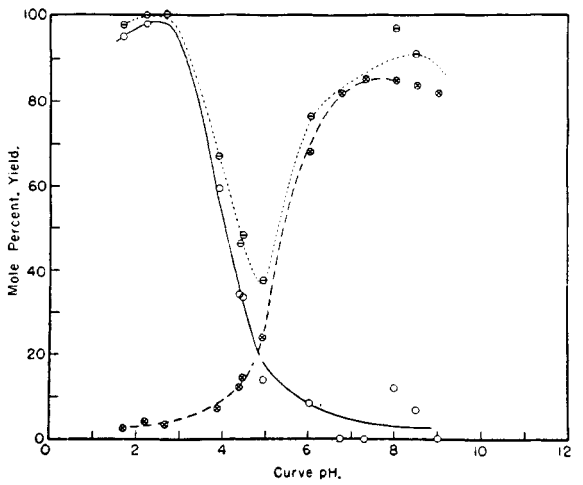


Fig. 12.—Variation of the mole per cent. yield of hydroquinone monosulfonate and hydroquinone disulfonate with *p*H for the reaction of sulfite and quinone monosulfonate. The sulfite–quinone monosulfonate ratio is 10. ○, hydroquinone monosulfonate; ⊗, hydroquinone disulfonate; ⊖, total accountable product.

Nature of the Intermediates.—The visual data indicate that the greenish-blue compound is most stable at a given *p*H when the sulfite–quinone ratio is unity, which leads to the tentative conclusion that it is a 1:1 compound or complex of sulfite and quinone. Sulfite, cysteine and glutathione all form stable 1:1 greenish-blue compounds with quinone; *l*-ascorbic acid forms a very transitory green or greenish-blue compound with quinone; and hydrazine forms a pink compound with quinone. It therefore appears that stable greenish-blue compounds are formed under the proper conditions of *p*H when quinone reacts with a reducing agent containing an oxidizable sulfur atom. It is known that molecules containing oxidizable sulfur atoms have a very strong tendency to dimerize from the free radical or semiquinone state to form disulfide linkages.

Quinone and hydroquinone in equivalent amounts form quinhydrone, under the proper conditions. The latter may be considered as dimer of two hydroquinone semiquinone molecules. It therefore appears that a hetero-dimer between the semiquinones of quinone and the sulfur-containing reducing agent may be the first step in the formation of the greenish-blue compounds. The greenish-blue compound of quinone and sulfite shows a positive deviation from Beer's law with increasing dilution, which indicates that it is not the original dimer, for then a negative deviation from Beer's law should result. The deviation does, however, indicate that an equilibrium or steady state is shifted by dilution. It is tentatively suggested that the dimer is the orange-pink substance and that the greenish-blue substance results from a molecular rearrangement, this rearrangement being facilitated by an increase in *p*H. The observation that the greenish-blue substance bleaches in the light and that this bleaching is accompanied by a decrease in *p*H suggests that the dimer loses a hydroxyl group when the rearrangement takes place. As shaking in air or addition of persulfate regener-

TABLE V

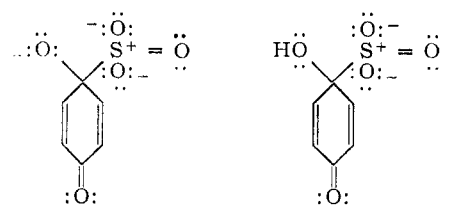
YIELDS OF PRODUCTS FOR REACTIONS OF SULFITE WITH QUINONE, QUINHYDRONE AND QUINONE MONOSULFONATE, RESPECTIVELY

Reactants	*p*H	Product yield	Intermediate	Life of intermediate
Hydroquinone, sulfite and oxidizing agent[a]	6–11	100% Hydroquinone monosulfonate	No direct evidence	
Quinone and sulfite	1–3	Sulfite/quinone = 1 75% Hydroquinone 22% Hydroquinone monosulfonate Sulfite/quinone = 10 60% Hydroquinone 30% Hydroquinone monosulfonate	Orange color appears near *p*H 2	Very short
	3–4.5	Hydroquinone decreases to 0%; hydroquinone monosulfonate increases to 100%	Orange color	Very short
	4.5–7.5	100% Hydroquinone monosulfonate	Orange color	Very short
	7.5–12.0	Hydroquinone monosulfonate decreases; some hydroquinone disulfonate appears; total accountable product decreases	Orange color precedes greenish-blue color	Life of orange color very short; stability of greenish-blue color increases with increase in *p*H
Quinhydrone and sulfite	1–8.5	After correction for hydroquinone yield is identical with the quinone sulfite reaction	No direct evidence	
	8.5–11.0	Hydroquinone monosulfonate increases to 100% of quinhydrone	No direct evidence	
	11.0–12	Hydroquinone monosulfonate decreases from 100 to 40%; hydroquinone disulfonate increases from 0 to 60%	No direct evidence	
Quinone monosulfonate and sulfite	2–5	Hydroquinone monosulfonate decreases from 100 to 20%. Hydroquinone disulfonate increases to 20%; total accountable product decreases to 40%	Yellow	Stability and strength increase with *p*H. Life of several seconds between *p*H 4.5 and 5.5
	5–8	Hydroquinone monosulfonate decreases to 2%; hydroquinone disulfonate increases to 90%; total accountable product increases to 90%	Yellow	Stability and strength rapidly decrease with *p*H
	8–10	Hydroquinone disulfonate slowly decreases	No direct evidence	

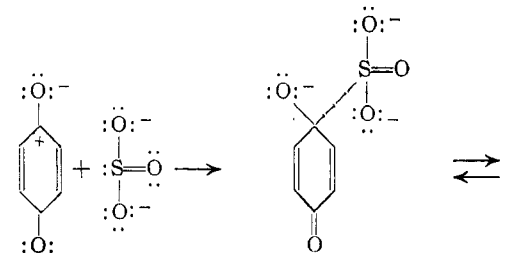
ates the greenish-blue compound, the molecular rearrangement must be accompanied by an oxidation–reduction reaction. As the greenish-blue substance has been formed under nitrogen in these Laboratories and under hydrogen by Pinnow,[4b] the original rearrangement may incorporate an internal oxidation–reduction reaction.

The nature and location of the original dimer bond is of importance. If the dimer bond is between sulfur in the sulfur-containing molecule and oxygen in the quinone, methylation of the ring should not hinder dimer formation; whereas, if the dimer bond involves the 1 or 4 carbon, methylation of the quinone ring should hinder dimer formation. The 2-, 3-, 5- and 6-positions in the ring are eliminated, as it is considered that addition at any one of these positions would lead to the monosulfonate. Sulfite and glutathione form a greenish-blue compound with *p*-benzo- and toluquinone, but not with 2,5-xylo- and duroquinone. Cysteine forms a greenish-blue compound with *p*-benzo-, tolu- and 2,5-xyloquinone, but not with duroquinone. The dimer bond is, therefore, probably made between the sulfur atom and the 1- or 4-carbon of the quinone ring.

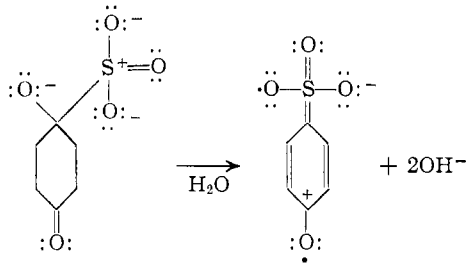
Van der Waals radii were used to draw projections of the molecules, and models were also made with Fischer–Hirschfelder atom models. The projections and the models support the reasoning of the preceding paragraph, and also indicate that the dimer is under considerable strain, which probably furnishes the driving force for the rearrangement. The dimer probably has one of these formulas



A probable mechanism for the reaction of sulfite and quinone to give the dimer, followed by a rearrangement and internal oxidation–reduction reaction to give the greenish-blue compound, is



First electron exchange Dimerization



Rearrangement

Similar formulas and mechanisms may be written for the reaction of quinone and sulfhydryl compounds. Kinetic studies are needed to deduce detailed mechanisms.

The yellow intermediate observed in the reaction of quinone monosulfonate and sulfite may be the semiquinone of quinone monosulfonate or a reaction product of quinone monosulfonate and sulfite. The data are insufficient to allow a decision; it is probable that it is the semiquinone.

The positive deviation of the greenish-blue substance from Beer's law, Table II, may be explained as follows: The concentration of the greenish-blue substance at any given moment depends upon the relative rates of the dimer oxidation reaction and the fading reaction. Fading always appears to take place within the solution faster than at the air–water interface; it thus appears that the fading reaction becomes predominant as the dissolved oxygen becomes depleted, and, therefore, the oxidation reaction eventually becomes limited by the rate of diffusion of oxygen across the air–water interface. Dilution effectively increases the oxygen supply in the partially oxygen-depleted solution and increases the total oxygen available per molecule of dimer; *i.e.*, the effective concentration of greenish-blue substance remains at a high level over a longer period of time.

It is known that when hydroquinone is oxidized in the presence of sulfite, the product is hydroquinone monosulfonate[3a,b,c]; similarly if cysteine or thioglycolic acid is present when hydroquinone is oxidized, the corresponding hydroquinone cysteine or hydroquinone thioglycolic acid is formed[3c]; *i.e.*, the sulfite, cysteine, or thioglycolic acid is always involved in an oxidation–reduction reaction. It has been shown in this paper that the reaction of quinone and sulfite also involves an oxidation–reduction reaction over the entire *p*H range. There is some evidence that the initial step is similar throughout the *p*H range 2 to 12; *i.e.*, that a one-electron exchange takes place followed by the formation of a hetero-dimer. This could by analogy with the aldehyde–sulfite addition product be classified as an addition reaction. However, the over-all reaction is one of oxidation–reduction; hence the hetero-dimer concept seems preferable. The green rearrangement product formed at high *p*H by sulfite, cysteine, glutathione, and very transiently by *l*-ascorbic acid serves to group all of these reactions together. The greenish-blue intermediate in all cases is light-sensitive and may be regenerated by oxidation, *e.g.*, shaking in air, *i.e.*, the greenish-blue substance has the properties that are commonly attributed to free radicals. The yellow intermediate that appears in the reaction of quinone monosulfonate and sulfite is probably the semiquinone of hydroquinone monosulfonate; it could, however, be a product of the reaction of quinone monosulfonate and sulfite.

The observation that hydroquinone oxidized at high *p*H in the presence of sulfite invariably yields hydroquinone monosulfonate coupled with the observations that quinone at these *p*H values yields a greenish-blue intermediate plus some hydroquinone monsulfonate and that quinhydrone at sufficiently high *p*H values yields 100% hydroquinone monosulfonate implies that the sulfite reacts with the semiquinone of hydroquinone or its dimer rather than with quinone.

The reaction of sulfite and aldehydes[7] is pictured as an addition reaction of sulfite to the carbonyl carbon. Condensation compounds of aldehydes and sugars with thiols are also pictured as addition reactions.[8] These reactions could be considered as one-electron exchanges followed immediately by formation of a dimer bond. This picture would also explain why these compounds are reversible.

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(7) (a) T. D. Stewart and L. H. Donnally, THIS JOURNAL, **54**, 3559 (1932); (b) W. M. Lauer and C. M. Langkammerer, *ibid.*, **57**, 2360 (1935).

(8) M. P. Schubert, *J. Biol. Chem.*, **111**, 671 (1935); **114**, 341 (1936); **130**, 601 (1939).