regardless of the rank or the type of these coals, the products are similar, and that the general properties correspond to condensed carbocyclic structures with paraffin side chains. Although it seems probable that this type of structure predominates, the presence of purely cyclic and paraffinic structures cannot be excluded.

The lower rank coal of high oxygen content gives on hydrogenation units which have, on an average, lower molecular weights than the units from higher rank coals of low oxygen content.

On hydrogenation, the extract and residue from the benzene extraction of coal give hydrocarbons which are similar in nature to those obtained from the hydrogenation of the unextracted coal.

The maximum yields of petroleum ether soluble products are obtained by hydrogenation of medium rank coals.

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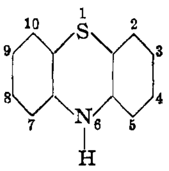
Another Type of Free Radical in the Group of Thiazines and Some Other Related Heterocyclic Rings

BY L. MICHAELIS, S. GRANICK AND M. P. SCHUBERT

Among the thiazine dyestuffs it was those with two auxochromic groups, such as thionine and methylene blue, for which formation of very stable semiquinone radicals in strongly acid solution was first discovered.[1] Later, certain thiazine-, oxazine-, and selenazine dyestuffs containing only one auxochromic group, either an amino group, or a hydroxyl group, were shown to be capable of forming semiquinone radicals even to a still higher extent.[2] Herefrom the problem arises how thiazine, oxazine, and selenazine[3] themselves, containing no auxochromic groups, behave. Our concern is essentially the problem whether there is a reversible univalent oxidation product, a free radical.

It has been shown by R. Pummerer and S. Gassner[4] and by Kehrmann and Diserens[5] that an oxidation product of thiazine on the oxidation level of a "meriquinone" easily can be obtained. A substance on a holoquinoid oxidation level can be prepared also. This holoquinoid product although easy to prepare in the form of its perbromide, is much less stable, and under our working conditions, by oxidizing the r-form in 80% acetic acid, has no noticeable stability at all. We are here mainly interested in the "meriquinoid" product and shall show that this is a free radical. If the two positions 3 and 9 (in formula I) are methylated, the radical is even more stable due to the blocking of the very reactive H atoms in para position to the N. Whereas the radicals of the thiazine dyes proper are formed only in rather



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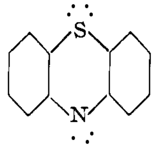

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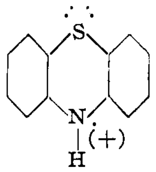

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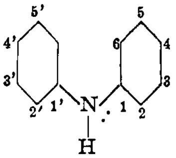

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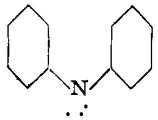

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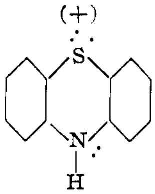

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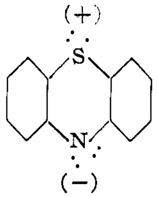

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[1] L. Michaelis, M. P. Schubert and S. Granick, THIS JOURNAL, **62**, 204 (1940).

[2] S. Granick, L. Michaelis and M. P. Schubert, *ibid.*, **62**, 1802 (1940).

[3] The parent substance or nucleus of a thiazine dye, stripped of all side chains is a substance which can exist in various oxidation levels. The fully reduced form is best known. It is thiodiphenylamine. An analogous name for the parent substance of the oxazines, namely, oxydiphenylamine, would be ambiguous. Bernthsen[3] [*Ber.*, **20**, 942 (1887)] for this reason named it phenazoxin. To avoid all difficulties in nomenclature we shall use the name *phenothiazine*, or even abbreviated, if no ambiguity arises, *thiazine*, for the parent substance, or skeleton, of the thiazine dyes and when we wish to distinguish the various reversible oxidation levels in which it may exist, we use the prefix r-, s-, or t-, for the reduced, semi-oxidized, and totally oxidized (quinonoid) forms, in the same way as for the dyestuffs themselves.[1] Then r-thiazine is the same as thiodiphenylamine. In the same sense we speak of r-, s-, and t-oxazine and selenazine.

[4] R. Pummerer and S. Gassner, *Ber.*, **46**, 2310 (1913).

[5] Kehrmann and Diserens, *ibid.*, **48**, 318 (1915).

concentrated solutions of sulfuric acid, the radical of thiazine itself, or oxazine or selenazine, is formed in (not at all necessarily water-free) acetic acid.

The structure of the radical derived from thiazine (I) may be considered either as II, which differs from I by an H atom; or as III, which differs from I by one electron only, and arises from II by addition of a proton in sufficiently acid solution. We designate II and III as s-thiazine. Thiazine, oxazine and selenazine behave quite analogously in this respect.

The next problem should be a comparison with respect to the formation of stable free radicals, of thiazine (or oxazine, or selenazine) with diphenylamine (IV) which differs from the others only by the lack of the S- (or O- or Se-) bridge. It is well known that Wieland[6] described the radical V which arises from dissociation of tetraphenylhydrazine. However, it should be emphasized that there is a very great difference indeed between the stability of this radical and those derived from thiazine, etc. Whereas the latter radicals can be obtained in a high concentration and in a quite stable condition in 80% acetic acid, the existence of diphenyl nitride can be asserted from indirect evidence rather than in any convincing direct way, its equilibrium concentration remaining extremely small even under most favorable conditions. The main evidence for the existence of this radical is the fact that a solution of tetraphenylhydrazine reacts with NO in a way which can be explained only by assuming a dissociation of the hydrazine into radicals analogous to the dissociation of hexaphenylethane. The radical derived from 4,4′-di-(methoxy)-diphenylamine is somewhat more stable and the radical from 4,4′ - bis - (dimethylamino) - diphenylamine (Bindschedler's green) is quite stable at least in organic solvents[7] and to a small, yet well measurable, extent even in aqueous solution.[8] These compounds show a behavior intermediate between diphenylamine, and those derivatives of thiazine containing auxochromic groups. As can be seen, the S-, O- or Se-bridge affords a surprisingly great stabilizing effect to the radical, and this effect will be accounted for in the discussion on the basis of the principle of resonance.

In addition, some free radicals derived from a few new compounds of thiazine will be described which have the property of not being further reversibly oxidizable to any quinonoid form of appreciable stability. The relation of these compounds to the parent substance, thiazine, is as follows. They contain side-chains consisting of tertiary amines such as pyridine, in the same position as the amino groups in Lauth's violet and are permanently stable in the form corresponding to the leuco compounds of other dyestuffs. In sufficiently acid solutions, they can be oxidized a single univalent step to form a rather stable s-form, a free radical, but no t-form or quinonoid form of any noticeable stability can be produced. This type of dyestuff was obtained by an extension of a method of synthesis according to Kehrmann and Karrer and will be described in the experimental part.

Discussion

The stability of these radicals can be accounted for by the principle of resonance, although only qualitatively at the present time, yet obviously in a very satisfactory way. The stability of the radical III, with a proton attached to the N, as it exists in sufficiently acid solution, can be explained by the resonance of this structure with another, such as VI. The resonance between these two limiting states III and VI corresponds to a symmetrically oscillating electric charge. In less acid solution, where no proton is attached to the N, the two limiting structures of the resonance would be II and VII. This resonance is no longer symmetric with respect to the distribution of the electric charge. The coulomb forces will tend to maintain essentially II, and counteract the separation of electric charges as they would be in VII. So, the superposition of the two states II and VII is such that VII probably contributes only a small share, the resonance is small, and the stability of the radical diminished. In this way the higher stability of the radical in acid solutions is understandable. The case is quite analogous for oxazine and selenazine, and at the same time shows why the stability of a radical is much smaller for diphenylamine, having no bridge atom to elicit a resonance of a comparable type.

After having shown that the resonance involving both N and S plays an important role in stabilizing the radical, we have to reconsider the

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[6] H. Wieland, *Ann.*, **381**, 212 (1911); H. Wieland and H. Lechner, *Ann.*, **392**, 156 (1912).

[7] H. Wieland, *Ber.*, **48**, 1087 (1915).

[8] G. Schwarzenbach and L. Michaelis, THIS JOURNAL, **60**, 1667 (1938).

case of the dyestuffs of the class containing one or two auxochromic groups. In the first paper on the radicals of the thiazines,[1] the resonance between the bridge N and N of one of the auxochromic groups was taken into consideration, making the case analogous to that of Wurster's dyes.[9] The fact that in a compound such as 3-hydroxythiazine a very stable radical can be obtained (2), showed that this explanation does not cover the whole situation. The present paper shows there is a chance of another type of resonance, which although not perfectly of the type formerly designated as "equivalent" is yet very efficient in stabilizing a free radical under such conditions of *p*H as to produce symmetry at least with respect to the distribution of the electric charge in the two limiting states which compose the resonating state. On the other hand, in the restricted resonance II $\longleftrightarrow$ VII a dipole moment oscillates between a certain finite value and zero, the direction of the dipole never changing its sign. This is much less favorable for resonance. In the radical of diphenylamine, there is no chance at all for any resonance of this particular type. The resonance energy, and its stabilizing effect, of diphenylamine can be increased by closing the ring with S, O or Se. It can also be increased by adding a third phenyl group without formation of any bridge, as can be seen from the stability of the cationic radical s-tritolyl amine[10] in the same way as the stability of the triphenylmethyl radical is conspicuously larger than that of diphenylmethyl, essentially due to the increase in the number of limiting structures which contribute a share to the true state.

An essential result of this discussion is that in the semiquinone radicals of the thiazine, oxazine and selenazine dyestuffs as they exist in very acid solution, the stabilizing effect is not solely attributable to a resonance of the type of Wurster's dyes, but also to resonance involving the two bridge atoms (N and S; or N and O; or N and Se). The latter type of resonance is sufficient to stabilize those radicals stripped of all auxochromic groups and thus lacking any similarity to the Wurster's radicals.

Thus the order of stability of the various radicals is quite compatible with our present notion, crude though it may be as yet, of resonance energy.

Experimental Part

I. Preparations.—Several of the preparations are parent substances of the compounds dealt with in the preceding paper[2] and have been accounted for therein. In addition we have some condensation products of the following type.

Kehrmann's[11] method of preparing methylene blue by the reaction between dimethylamine and "phenazthionium perbromide" (in our nomenclature, t-thiazine perbromide) is one of great chemical interest. The same method can be applied to other amines so that a variety of substitution products of Lauth's violet can be made. Karrer[12] has extended the reaction to include analogous compounds of selenazine. We may add another curious and unexpected extension of this reaction. Even pyridine, a tertiary amine, reacts with t-thiazine perbromide. The reaction is very rapid and gives a red crystalline product which is on the same oxidation level as leucomethylene blue, not on that of methylene blue. This compound, 3,9-bis-pyridinium-r-thiazine (formula 8) is easily soluble in water with an intensely yellow color, exhibiting no definite absorption band in the visible spectrum. The color appears unaffected by acid or alkali. A compound with Se instead of S, and another with nicotinic acid amide instead of pyridine, can be made quite analogously. With trimethylamine, t-thiazine perbromide also reacts but the product seems to decompose easily in hot water producing a strong odor of formaldehyde.

3,9-bis-Pyridinium-r-thiazine.—Five grams of freshly prepared phenazthionium perbromide[13] (in our nomenclature t-thiazine perbromide) suspended in 15 cc. of methanol is ground up well with 8 cc. of pyridine. The reaction product crystallizes out rapidly. The mixture is diluted with 25 cc. of ether, chilled and filtered. The crude product is dissolved in 50 cc. of cold water, filtered and the product is precipitated with 250 cc. of acetone. The yield is 2.0 g. of red crystals, which dissolve in water with yellow color; no m. p. up to 298°. *Anal.* Calcd. for $C_{22}H_{17}N_3SBr_2{\cdot}2H_2O$: N, 7.62; S, 5.81; Br, 29.05. Found: N, 7.64; S, 5.67; Br, 29.5.

3,9-bis-Pyridinium-r-selenazine.—The analogous selenium compound is made similarly. *Anal.* Calcd. for $C_{22}H_{17}N_3SeBr_2{\cdot}2H_2O$: N, 7.02; Br, 26.85. Found: N, 7.07; Br, 26.79.

3,9 - bis - (β - Carbaminopyridinium) - r - thiazine.—Five grams of freshly prepared thiazine perbromide, 6 g. of nicotinic acid amide, 15 cc. of methanol and 25 cc. of ether were cooled on ice, filtered, washed with ether, dissolved in 50 cc. of hot water, filtered quickly, 600 cc. of acetone added, and iced; recrystallized from 100 cc. of hot water plus 100 cc. acetone, yield 1.5 g. *Anal.* Calcd. for $C_{24}H_{19}N_3SBr_2$: N, 11.63; S, 5.33; Br, 26.62. Found: N, 11.39; S, 5.19; Br, 26.42. The nitrogen in these compounds could be determined easily by the Dumas method.

II. The Behavior of Individual r-Compounds on Oxidation.—We consider as evidence for the formation of a free radical the appearance of a univalent potentiometric oxida-

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(9) L. Michaelis, M. P. Schubert and S. Granick, THIS JOURNAL, **61**, 1981 (1939).

(10) S. Granick and L. Michaelis, *ibid.*, **62**, 2241 (1940).

(11) F. Kehrmann, *Ber.*, **49**, 53 (1916).

(12) P. Karrer, *ibid.*, **51**, 190 (1918).

(13) F. Kehrmann, *ibid.*, **43**, 53 (1916).

tive titration curve, with index potential sufficiently close to 28.6 millivolt at 30°, and a recognizable end-point of this univalent titration, when the substance in its r-form is titrated with a suitable oxidizing agent in a suitable solvent at constant *p*H. Since many such titration curves have been reproduced in all detail in the preceding papers, we may confine the description of the experiments to a few remarks and present the absorption bands of the radicals in Fig. 1.

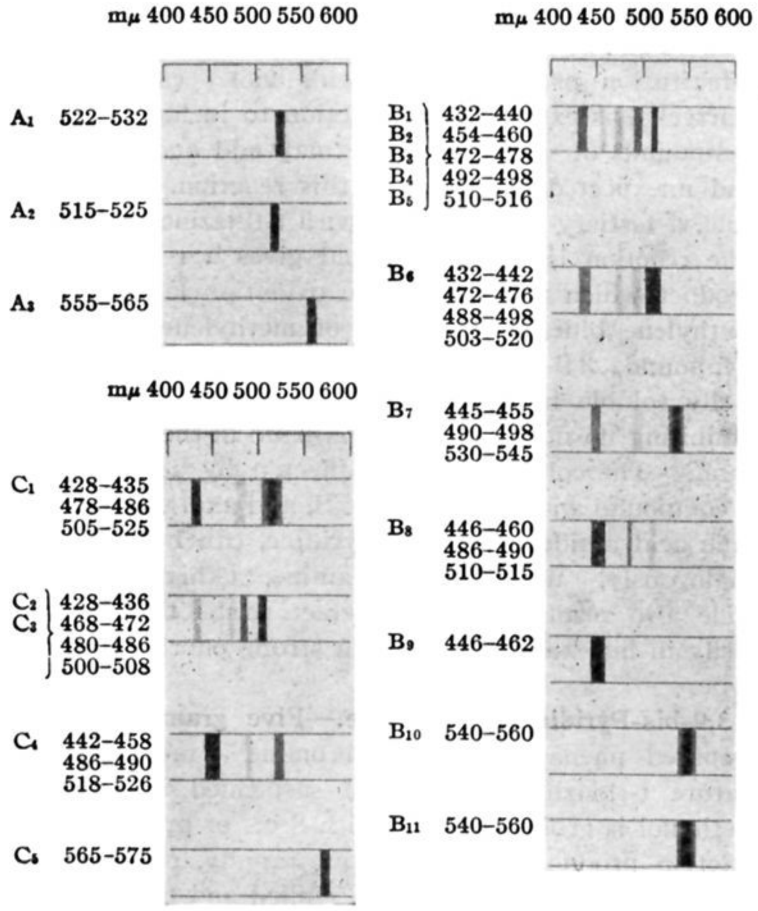


Fig. 1.—Sketches of absorption spectra made from observations with the hand spectroscope, of the radicals derived from oxazines (A_1 to A_3), thiazines (B_1 to B_{11}), and selenazines (C_1 to C_5). Those marked with * are taken from the earlier papers.[1,2] Solvents were used in which the radicals remained most stable. Compounds A_1, B_1, B_6, B_7, and C_1 were prepared from their r-forms by oxidizing with Br_2 in 80% acetic acid aqueous solution. The other compounds were prepared from their quinonoid form by reducing with titanous sulfate in 10 to 20 *N* H_2 solution, the concentration depending on the particular compound. The sketch of the group B_1 is schematized, there being slight variation in the relative intensities of the bands depending on the particular compound. A_1, oxazine; A_2, 3,9-diaminoöxazine*; A_3, 3 hydroxyoxazine*; B_1, thiazine; B_2, 3-aminothiazine*; B_3, 3,9-aminothiazine (thionine)*; B_4, methylene blue*; B_5, 3,9-bis-(phenylamino)-thiazine*; B_6, N-methylthiazine; B_7, 3,9-dimethylthiazine; B_8, 3,9-bis-(pyridinium)-thiazine; B_9, 3,9-bis-(β-carbaminopyridinium)-thiazine; B_{10}, 3-hydroxythiazine*; B_{11}, 3-hydroxy-9-aminothiazine*; C_1, selenazine; C_2, 3,9-diaminoselenazine*; C_3, 3,9-bis-(dimethylamino)-selenazine*; C_4, 3,9-bis-(pyridinium)-selenazine; C_5, 3-hydroxyselenazine*.

1. (Figure 1, A_1) **r-Oxazine.**—The radical derived herefrom is less stable than that of thiazine. A 2 × 10^{-4} *M* solution in 90% acetic acid (by volume) is titrated with lead tetraacetate dissolved in the same solvent. Only the first half of the expected univalent titration curve shows sufficiently stable potentials. Extrapolating this curve and considering the titer of the lead tetraacetate solution, we find E_i = 26 mv. (sufficiently close to the expected 28.6). The normal potential of this step of oxidation is +0.724 volt, and the color of the radical purple.

2. (Figure 1, B_1) **r-Thiazine.**—On oxidizing a 2 × 10^{-4} *M* solution in 50% acetic acid with lead tetraacetate, or with bromine, dissolved in the same solvent, a very distinct univalent oxidative titration curve is obtained. Only at the end do the potentials drift somewhat. E_i in onee xperiment 27.5, resp., 28.5 mv.; in another with 90% acetic acid 29.0, resp., 27.5 mv. Normal potential of this step in 90% acetic acid is +0.701 volt; color of the radical orange-pink.

3. (Figure 1, B_7) **r-3,9-Dimethylthiazine.**—Under the same conditions as the preceding compound, the potentials are steady to the very end of a univalent oxidation, the end-point is sharp. In 90% acetic acid, titrated with bromine, E_i = 29.6, 29.8; normal potential +0.626 volt. Titrated with lead tetraacetate, E_i = 29.0, 28.0; normal potential +0.62 volt. The radical is reddish-pink.

4. (Figure 1, B_6) **r-N-Methylthiazine.**—The radical can be obtained even in neutral solution, although it has, then, only a short lifetime. (Oxidizing with bromine in equal volume of phosphate buffer *p*H 6.8 and methanol.) In more acid solution, it is much more stable. Titration of a 2 × 10^{-4} *M* solution in 80% acetic acid with bromine gives a satisfactory univalent curve, E_i = 29.0, 29.8 mv.; normal potential +0.829 volt. Titration in 90% acetic acid with lead tetraacetate gives a good curve with very satisfactory end-point of titration. E_i = 29.2, 29.4; normal potential is 0.882 volt. The radical is pinkish-red.

5. (Figure 1, C_1) **r-Selenazine.**—In 90% acetic acid, titration with lead tetraacetate shows a univalent titration curve, with some drift of the potentials toward the end; E_i = 30, 30 millivolts; normal potential 0.769 volt. The radical is orange-yellow.

6. (Figure 1, B_8) **3,9-bis-Pyridinium-r-thiazine.**—The r-form, red in the crystalline state, gives a yellow solution with diffuse absorption in the blue without any definite band in the visible. Titration in 4.5 *N* sulfuric acid gives a poor titration curve, the labile blue-green step of oxidation arises early. Titration (2 × 10^{-4} *M* solution) in 18.9 *N* sulfuric acid with potassium dichromate dissolved in the same solvent yields a good curve, potentials drifting only very slowly toward the positive side. The blue-green labile compound does not arise. Color turns during the titration from yellow to intense orange-brown. After adding one equivalent of oxidizing agent, there is a sharp end-point of titration. E_i = 31, 30 mv. Normal potential of this univalent step of oxidation is +0.43 volt. Titration beyond this end-point gives very unstable potentials. The color of the radical is deep yellow-brown.

7. (Figure 1, B_9) **3,9-bis-(β-Carbamino-pyridinium)-r-thiazine** (formula 7).—Quite similar to No. 6. In 18.9 *N* sulfuric acid, titration with potassium dichromate, gives very slightly drifting potentials and a sharp end-point after one equivalent of oxidation; E_i = 29, 32. Normal potential is +0.416 volt and color of the radical deep yellow-brown.

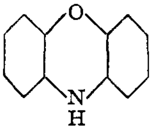
8. (Figure 1, C_4) **3,9-bis-Pyridinium-r-selenazine** (formula as for B_8 with Se instead of S). Color of r-form, yellow; no bands. Color of the radical yellow-brown.

Rules Concerning the Absorption Spectrum of the Radicals.—Although we are still very far from accounting quantitatively for the absorption spectra of the various radicals on any theoretical basis, there are certain regularities which are worth mentioning.

1. The radicals of the oxazines all show one single absorption band in the visible, with a peak somewhere between 520 and 560 according to the presence and nature of side chains.

2. For the thiazines no such simple rule exists; rather there are two types of absorption spectrum for the radical. The majority of the thiazine radicals show a complicated series of bands and the absorption spectrum is very little dependent on the number and nature of the side chains. For instance, the radical of the unsubstituted thiazine is almost undistinguishable from that of methylene blue. Only the 3-hydroxy compounds resemble the oxazine compounds by showing one single absorption band, and this seems to hold, whether the 3-hydroxy group is the only substituent in the thiazine nucleus or not. The nicotinic acid condensation product of thiazine also shows a single band, whereas the pyridine condensation product is of a transitional type insofar as there are indeed secondary bands in addition to the main band, but very faint.

3. The selenium compounds, according to the experience available so far, show precisely the same behavior as the thiazines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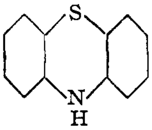
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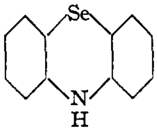
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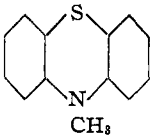
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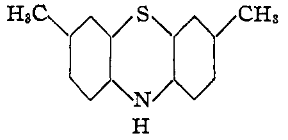
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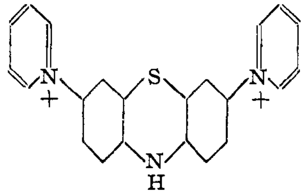
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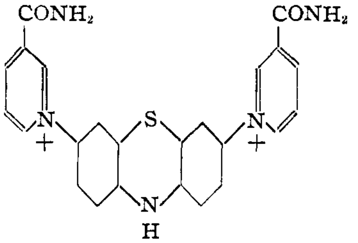
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Summary

The parent substance of the thiazine dyestuffs, thiodiphenylamine, yields on oxidation in 50 to 80% acetic acid a rather stable univalent oxidation product, a free radical. The same holds for the parent substances of the oxazines and selenazines, but not for diphenylamine the radical of which is very considerably less stable. It is shown that the S-bridge (or O- or Se-bridge) makes possible a particular kind of resonance as a stabilizing factor for the free radical. This type of resonance is somewhat different from the one originally suggested for the radicals of thiazine dyestuffs. Furthermore, a few dyestuffs of this group are described which are stable compounds only in their leuco form (r-form), and in the form of the free radical (s-form), but not in the holoquinoid form (t-form).

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