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RADICAL REACTIONS OF THIOAMIDES, THIOUREAS, AND RELATED COMPOUNDS

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Recent studies on novel reactions of thioamides, thioureas, and related compounds with various radical-forming agents such as phenylazotriphenylmethane, *N*-nitrosoacetanilides, and aryldiazonium salts are reviewed. The aryl radicals are shown to add to the sulphur atom of the fragments NH—CS—R or NH—CS—NH forming the adduct radicals NH—Ċ(SAr)—R and NH—Ċ(SAr)—NH, respectively. This is proven by isolation of the reaction products and by ESR spectroscopy. The main pathways of the adduct-radicals' transformations are the following: (i) Cross-disproportionation with other radicals due to hydrogen abstraction from an NH group yielding the *S*-aryl derivatives of isothioamides and isothioureas. (ii) Cross-disproportionation due to hydrogen abstraction from an α-CH group affording ketene *N,S*-acetals. (iii) "Growth" with the formation of bis-formamidine sulfides and bis-imidosulfides. (iv) Oxidation by Cu^{II} to isothiouronium salts. Some relations which permit to predict the reaction pathway depending on the properties of the parent compounds are formulated. The radical arylation of the aromatic thioamides and some thioureas is shown to be a facile preparative method for the synthesis of the corresponding *S*-arylisothioamides and -isothioureas. The mass spectrometric behavior of the aromatic thioamides has been studied. The main fragmentation and rearrangement pathways under electron impact have been determined.

CONTENTS

I. INTRODUCTION

Organic compounds of bivalent sulfur may formally be classified as those containing dicoordinated sulfur (thiols, sulfides, di- and polysulfides, derivatives of sulfenic acids, etc.) and monocoordinated sulfur (thiocarbonyl compounds such as thioketones, derivatives of thiocarbonic and thiocarboxylic acids).

Radical reactions of the compounds of the first type have been studied for many years; they comprise, mainly, various transformations of thiols and sulfides: addition, telomerization, rearrangements, and so on.[1] Recently this field was enriched by numerous papers dealing with radical substitution at a sulfur atom in sulfides and disulfides.[2-7]

Radical reactions of thiocarbonyl compounds had been little studied until recently although these compounds are rather widely used in processes for which a radical mechanism has been postulated: rubber vulcanization,[8] corrosion,[9] reactions induced by ionizing radiation,[10] and others.

Naturally, because of the lack of detailed data on the routes and products of transformations of thiocarbonyl compounds, their role in radical reactions has been formulated only in general terms. In the last decade it has been shown (due to the use of the ESR method) that a thiocarbonyl group is a rather effective trap for radicals. It has been reported that many organic and organoelement radicals are capable of adding to a thiocarbonyl group of carbon disulfide, thioketones, trithiocarbonates, and trithianes.[11-14]

The data on the structures of the intermediate adduct radicals are, however, rather contradictory; besides, only limited information is available on further routes of their transformation.

In this report our recent results on radical arylation and some other radical reactions of compounds containing the S=C—NH— group (thioamides, thioureas, and their derivatives) are summarized. The compounds proved to be rather reactive in radical

reactions. A special interest in the compounds of this type was aroused due to their polyfunctional nature which ensures high potentialities in synthesis. It is also important that the compounds are easily accessible and well studied in various ionic reactions.

II. RADICAL ARYLATION OF COMPOUNDS CONTAINING THE HN—CS—R OR HN—CS—NH FRAGMENT

II.1. Sources of Aryl Radicals

A choice of the sources of aryl radicals is very important in designing radical arylations of the above-mentioned thiocarbonyl compounds. First, it must be rigorously proven that decomposition of the radical-forming agents yields aryl radicals. Second, in accordance with the problem stated, the aryl radicals must be obtained at relatively low temperatures since many arylation products, especially free *S*-arylisothiouronium compounds, are thermally unstable. In addition, the radical-forming agents must be sufficiently accessible and safe in handling.

Due to the above, we have chosen phenylazotriphenylmethane (PAT), *N*-nitrosoacetanilide (NAA),† and aryldiazonium salts in combination with $CuCl_2$ as sources of aryl radicals.

PAT is a traditional source of phenyl radicals.[15] It decomposes smoothly at 50–60°C according to the reactions:

$$PhN{=}NCPh_3 \longrightarrow Ph^{\bullet} + N_2 + \dot{C}Ph_3 \qquad (1)$$

One disadvantage of PAT is that trityl radicals of low reactivity, formed concomitantly with the phenyl radicals, do not react with thiocarbonyl compounds and thus contaminate the reaction mixture with the products of their transformations.

NAA is also a traditional radical-forming agent.[16] It decomposes in solution at room temperature. The mechanism of NAA decomposition has been intensively studied in recent years and there are no doubts that the decomposition results in the formation of radicals; this has been shown both by chemical and ESR methods.[17] Two routes of the reaction are possible as expressed by the summarized eqs. (2) and (3):

$$2\ CH_3CON(NO)Ph \longrightarrow Ph^{\bullet} + N_2 + PhN{=}N{-}O^{\bullet} + (CH_3CO)_2O \qquad (2)$$

$$CH_3CON(NO)Ph \longrightarrow Ph^{\bullet} + N_2 + CH_3COO^{\bullet} \qquad (3)$$

It seems quite likely that the mechanism of NAA decomposition is dependent on the particular conditions and the presence of other components in the reaction mixture. NAA can successfully be used for arylation of aromatic thioamides and thioureas, but proved inapplicable of the arylation of easily oxidized compounds. For instance, in its reaction with 2-thiopyridone[18] it is reduced with the formation of acetanilide and

† In some cases *N*-nitrosoaceto-*p*-toluidide (NAT) was also used.

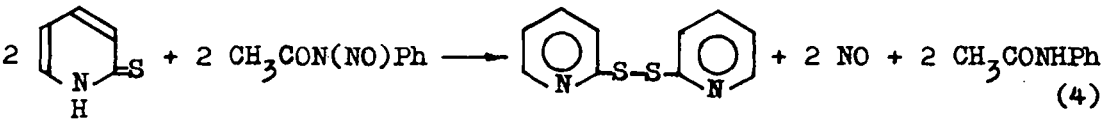
TABLE I

ESR Parameters[a] for the Nitroxyls $ArN(\dot{O})R$ Formed in the Reactions of ArN_2BF_4 with Copper and its Salts in the Presence of Nitroso Compounds RNO[21,22]

Ar	R	a_N	a_H^p	a_H^o	a_H^m
C_6H_5	$(CH_3)_3C$	13.3	2.0	2.0	0.9
C_6H_5	$2,3,5,6\text{-}(CH_3)_4C_6H$	10.1	2.8	2.8	1.0
$p\text{-}NO_2C_6H_4$	$(CH_3)_3C$	10.4		2.5	0.7
$p\text{-}CH_3OC_6H_4$	$(CH_3)_3C$	13.1		2.2	0.6
$p\text{-}CH_3OC_6H_4$	$2,3,5,6\text{-}(CH_3)_4C_6H$	10.5		2.8	

[a] Coupling constants in gauss.

nitrogen oxide according to:



(4)

Aryldiazonium salts as sources of aryl radicals deserve special attention. There are many literature data which indicate that interaction of aryldiazonium salts with copper salts yields aryl radicals,[19] although such reactions are sometimes interpreted as ionic.[20] Investigation of the reaction between ArN_2BF_4 ($Ar{=}C_6H_5$, $p\text{-}NO_2C_6H_4$, $p\text{-}CH_3OC_6H_4$) and copper chloride or metallic copper by the ESR method made it possible to answer this question unambigously.[21,22] With the use of nitroso-*t*-butane (NtB) and nitrosodurene (ND) as spin traps it was possible to detect the formation of aryl radicals in all cases. The ESR spectral parameters of the corresponding spin adducts are given in Table I and agree completely with the literature data.[23,24] The ESR spectra recorded do not depend on whether copper or its salts are used as a catalyst; the only difference observed is that between the rates of the formation of aryl radicals. The highest rate is observed in the reaction with metallic copper and the lowest one in that with $CuCl_2$. Thus, the reaction can be described by the equation:†

$$ArN_2^+ + Cu^n \longrightarrow Ar^\bullet + N_2 + Cu^{n+1} \qquad (n = 0,1) \qquad (5)$$

As will be shown below (see Section II.3.1) radical arylation of some thioureas with phenyl- and, in particular, *p*-nitrophenyl-diazonium tetrafluoroborate takes places in the absence of copper salts. Taking into account the very high nucleophilicity of thioureas, one may assume that they, similarly to other nucleophilic compounds (such as KOH), can decompose aryldiazonium salts by the radical mechanism. To confirm this assumption, the spin trapping technique was applied to the study of the reactions of thiourea,

† In acetone solution Cu^{II} is reduced to Cu^{I} [25].

TABLE II

ESR Parameters[a] for Nitroxyls $ArN(\dot{O})Bu^t$ Formed in the Reactions of ArN_2BF_4 with Thiourea and its Derivatives in the Presence of NtB[26,27]

Thioureas	Ar	a_N	a_H^p	a_H^o	a_H^m
Thiourea	C_6H_5		No signal		
Thiourea	p-$NO_2C_6H_4$	10.3[b]		2.5	0.7
N-Allylthiourea	C_6H_5[c]	12.2	2.0	2.5	0.9
N-Allylthiourea	p-$NO_2C_6H_4$[d]	10.3[b]		2.5	0.7
Thiosemicarbazide	C_6H_5		No signal		
Thiosemicarbazide	p-$NO_2C_6H_4$	10.3[b]		2.5	0.7

[a] Coupling constants in gauss.
[b] $a_N NO_2 = 1.0$.
[c] $C_6H_5SN(\dot{O})Bu^t$, $a_N = 16.6$ is also formed.
[d] p-$NO_2C_6H_4SN(\dot{O})Bu^t$, $a_N = 15.8$ is also formed

N-allylthiourea, and thiosemicarbarbazide with ArN_2BF_4 (Ar=C_6H_5, p-$NO_2C_6H_4$). It turned out that in some cases aryl radicals are formed (Table II).[26,27] N-substituted thioureas were shown to be more effective than thiourea and p-$NO_2C_6H_4N_2BF_4$ was demonstrated to form radicals more readily than $C_6H_5N_2BF_4$.[26]

Thus, it may be considered to be proven that decomposition of aryldiazonium salts in the presence of copper chlorides gives aryl radicals. When arylation occurs in the absence of copper salts a special investigation is necessary to prove the radical mechanism.

Arylation with aryldiazonium salts has some advantages. First, it allows to vary the nature of the substitutents on the aromatic ring due to the ready accessibility of the corresponding starting compounds; second, arylation of thioureas yields directly thermally stable *S*-arylisothiouronium salts rather than unstable free bases. The method has, on the other hand, the disadvantage that the reactions must be carried out in a water-acetone medium in the presence of copper salts which in some cases results in hydrolysis of the initial or final compounds, formation of products of their condensation with acetone, and copper complexes of organosulfur compounds with different composition.[27,28]

II.2. Radical Arylation of Thioamides

Recent reviews devoted to thioamides[29] contain comprehensive data on all their reactions except radical ones which are not mentioned at all[†] although a thioamide molecule has at least three reactive centers which are potentially suitable for a radical attack (C=, N̈, S̈).

Therefore, it was of interest to study the possible interactions between thioamides and radicals. In our papers[30–32] we studied the reactions of aromatic thioamides

[†] Some information about the radical reactions of thiomides can be found in a recent review[29c] which contains references to our work published in 1978–1980. These data are discussed below in detail.

Ar—CS—NHAr′ with phenyl radicals. The problem of determining the site of the radical attack and the reaction route depending on the structure of the initial thioamide was considered of primary importance.

II.2.1. Aromatic Thioamides The results obtained are shown in Table III. It is seen that the radical arylation of thioamides proceeds regioselectively: in all cases phenyl is added to a sulfur atom. The main pathway of this reaction is illustrated by Scheme 6:

$$\mathrm{Ar{-}\overset{\overset{\mathrm{S}}{\|}}{C}{-}NHAr'} \xrightarrow{Ph^{\bullet}} \mathrm{Ar{-}\overset{\overset{\mathrm{SPh}}{|}}{C}{=}NAr'} \qquad (6)$$

This is testified by the formation of *S*-arylated products in high, often close to quantitative, yield. In the reaction series studied such results were obtained independent of the polarity of the substituents both on carbonyl- and amide-linked aromatic rings. The yield of arylation products decreases only when the initial thioamide contains substituents easily attacked by phenyl radicals, namely, benzylic hydrogen or iodine (Table III, Nos. 5 and 12).

The results obtained show that radical phenylation may be a convenient model for studying radical reactions at a C=S group and a preparative method for the synthesis of *S*-phenylisothioamides. Earlier these compounds were prepared, as a rule, from amides in two steps[33]:

$$\mathrm{R{-}\overset{\overset{\mathrm{O}}{\|}}{C}{-}NHR'} \xrightarrow[\text{or } PCl_5]{SOCl_2} \mathrm{R{-}\overset{\overset{\mathrm{Cl}}{|}}{C}{=}NR'} \xrightarrow[-\ NaCl]{ArSNa} \mathrm{R{-}\overset{\overset{\mathrm{SAr}}{|}}{C}{=}NR'} \qquad (7)$$

TABLE III

Radical Phenylation of Thiobenzanilides (in acetone, 20 °C, 20 h[31,32,33])

$$\mathrm{Ar{-}\overset{\overset{\mathrm{S}}{\|}}{C}{-}NHAr'} \xrightarrow{NAA} \mathrm{Ar{-}\overset{\overset{\mathrm{SPh}}{|}}{C}{=}NAr'}$$

No.	Ar′	Ar	Yield of *S*-phenyl-isothiamide, %
1	C_6H_5	C_6H_5	85
2	*p*-BrC_6H_4	C_6H_5	91
3	*p*-$NO_2C_6H_4$	C_6H_5	93
4	*p*-$CH_3OC_6H_4$	C_6H_5	76
5	*p*-$CH_3C_6H_4$	C_6H_5	49
6	C_6H_5	*p*-ClC_6H_4	80
7	C_6H_5	*p*-$CH_3OC_6H_4$	92
8	C_6H_5	*p*-$NO_2C_6H_4$	100
9	C_6H_5	*o*-ClC_6H_4	96
10	C_6H_5	*o*-$CH_3C_6H_4$	99
11	C_6H_5	*o*-BrC_6H_4	90
12	C_6H_5	*o*-IC_6H_4	36
13	C_6H_5	*o*-$CH_3CO_2C_6H_4$	75

TABLE IV

Radical Phenylation of Thioamides R—CS—NHR′(in acetone, 20 °C, 20 h[18])

No	R	R′	Conversion of thioamide, %	Yields, % of theory	
				R—C(SPh)=NR′	Ph_2S_2
1	C_6H_5	$CH(CH_3)_2$	100	88	trace
2	C_6H_5	$CH_2CH(CH_3)_2$	100	53	12
3	*p*-ClC_6H_4	$CH_2CH(CH_3)_2$	87	68	5
4	*p*-$CH_3OC_6H_4$	$CH_2CH(CH_3)_2$	95	69	10
5	C_6H_5	*cyclo*-C_6H_{11}	88	71	trace
6	C_6H_5	$CH_2C_6H_5$	84	67	trace
7	CH_3	C_6H_5	88	71	0
8	CH_3	$CH_2C_6H_5$	65	0	34
9	CH_3	C_4H_9	60	0	49[a]
10	2-Thiopyrrolidone			0	56
11	2-Thiopiperidone			0	50
12	Thiocaprolactam			0	52

[a] Ph_2S (~7%) is also formed

II.2.2. Aliphatic and Cyclic Thioamides When passing from aromatic thioamides to those with alkyl substituents in the acyl or amide part of the molecule, the situation becomes more complex.[18] Table IV illustrates the outcome of the reactions of such thioamides with NAA. As is seen from Table IV, radical arylation of thioamides of the above type is accompanied by the formation of diphenyl disulfide and diphenyl sulfide. In the reactions of thioamides containing alkyl substituents in both parts of the molecule or in those of cyclic thioamides, diphenyl disulfide is the main sulfur-containing product.

The structure of all compounds obtained was ascertained by NMR and mass spectroscopy and, in many cases, by comparison with authentic samples obtained independently.[18,30-32]

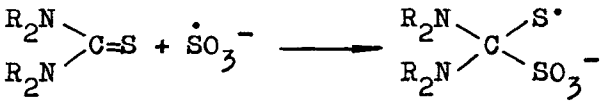
It is important to emphasize here (for a detailed discussion of the mechanism, see Section III) that high yields of *S*-phenylisothioamides in radical phenylation are obtained when in the initial thioamide the thiono group is conjugated with an aromatic ring (Table III, Table IV, Nos. 1–6) and/or when the NH group contains an aromatic substituent (Table IV, No. 7). It should also be mentioned that in the reactions yielding partially or predominantly other products than isothioamides (Table IV, Nos. 2–4, 8–12), phenyl radicals are always scavenged by the sulfur atom.

II.3. Radical Arylation of Thiourea and Related Compounds

Thiourea, its derivatives, and analogs are the most important compounds of organosulfur chemistry widely used in the synthesis of diverse organosulfur compounds,[10]

in particular, heterocycles.[34] They also play an important role in many biochemical processes (see, for instance, Ref.[35]).

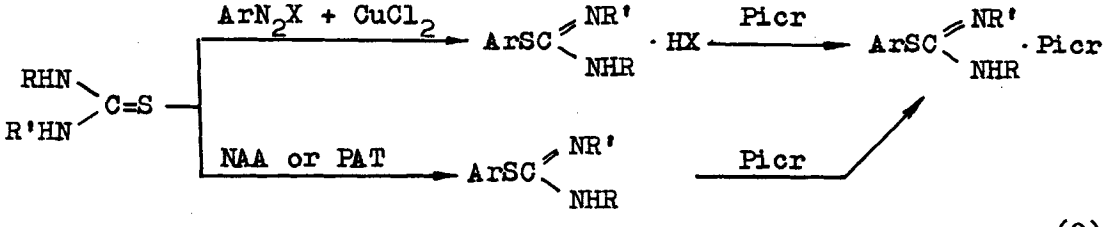
Whereas ionic reactions of thioureas have been studied comprehensively,[10] literature data on radical reactions are scarce and include, for instance, reports about interaction of thiourea and some of its derivatives with radicals of proteins and peptides,[36] uracyl radicals,[37] and the anion radical $\dot{S}O_3^-$.[38] All these reports, however, contain no information about the study and isolation of reaction products. It was assumed that $\dot{S}O_3^-$ is added not to a sulfur, but to a carbon atom.[38] It was of interest to find out whether the features observed for the radical arylation can be generalized also for the thiourea series in which four reactive centers (C=, N̈R, N̈R′, S̈) are present.



(8)

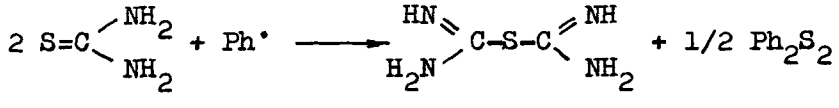
It turned out that the arylation of such compounds proceeds similarly to the arylation of thioamides although there are some essential differences. The similarity is that in all cases studied (thiourea, its phenyl, diphenyl, acetyl, and allyl derivatives, thiosemicarbazide, and acetone thiosemicarbazone) the aryl radical is added to the sulfur atom of the C=S bond (see Tables V–VII). The differences are, mainly, due to the fact that the *S*-arylisothiouronium compounds formed are much more labile than isothioamides and can, as a rule, be isolated only as salts (picrates). Sometimes the arylation products undergo secondary transformations even at 20 °C (see Section V).

II.3.1. Thiourea, N-Phenyl- and N,N′-Diphenylthiourea, Thiosemicarbazide, and Acetone Thiosemicarbazone In this Section we consider thiourea and its derivatives which, after radical arylation, form the relatively stable *S*-arylthiouronium compounds. Such examples are the reactions of thiourea, *N*-phenyl and *N,N′*-diphenylthiourea, thiosemicarbazide, and acetone thiosemicarbazone with aryldiazonium salts, NAA, and PAT (Tables V–VII). In the general case the reaction can be described by the Scheme:



(9)

In the arylation of thiourea (Table VII, Nos. 1, 2) the formation of bis-formamidine sulfide as side or main reaction product is also observed:†



(10)

† The mechanism of this reaction is considered in detail in Section III.5.1.

TABLE V

Radical Arylation of Thiourea with Aryldiazonium Salts (in water)[39]

$$S{=}C(NH_2)_2 + p\text{-}XC_6H_4N_2Y \xrightarrow[Picr]{CuCl_2} p\text{-}XC_6H_4SC(=NH)NH_2 \cdot Picr$$

No	X	Y	Yields, % of theory: *S*-arylisothiouronium picrates	Yields, % of theory: accompanying products	
1[a]	H	BF_4	27	$H_2N{-}C(=NH){-}S{-}C(=NH){-}NH_2$	2
2	CH_3	BF_4	11		
3	NO_2	BF_4	63		
4	Cl	BF_4	15	$H_2N{-}C(=NH){-}S{-}C_6H_4{-}S{-}C(=NH){-}NH_2$	1
5	H	Cl	20		
6	CH_3	Cl	10–18		
7	NO_2	Cl	30		
8	Cl	Cl	35		

[a] See Ref. [40]

Table V illustrates that the yield of *S*-arylisothiouronium salts increases when the arylation is performed with diazonium salts containing electron-attracting substituents in the ring. The formation of *p*-phenylenediisothiouronium dipicrate in the arylation of thiourea with *p*-chlorophenyldiazonium tetrafluoroborate (Table V, No. 4) indicates that in this case the reaction is accompanied, to a small extent, by nucleophilic replacement of chlorine with an isothiouronium moiety.

TABLE VI

Arylation of *N*-Substituted Thioureas $RHN{-}CS{-}NH_2$ with $p\text{-}XC_6H_4N_2BF_4$ (in acetone)[27]

No	R	X	Catalyst	Reaction products (picrates)	Yield, %
1	NH_2	H	$CuCl_2$	$H_2N{-}N{=}C(SPh)NH_2$	90
2	NH_2	NO_2	—	$(CH_3)_2C{=}N{-}N{=}C(SC_6H_4NO_2)N{=}C(CH_3)_2$	100
3	$N{=}C(CH_3)_2$	H	$CuCl_2$	$(CH_3)_2C{=}N{-}N{=}C(SPh)NH_2$	50
4	$N{=}C(CH_3)_2$	NO_2	—	$(CH_3)_2C{=}N{-}N{=}C(SC_6H_4NO_2)NH_2$	54
5[a]	Ph	H	$CuCl_2$	$PhN{=}C(SPh)NH_2$	60

[a] See Ref.[40]

TABLE VII

Radical Arylation of Thioureas RHN—CS—NHR′ with Various Radical Forming Agents (in acetone)

No.	R	R′	Source of phenyl radicals	Reaction products (yield in %)	Ref
1[a]	H	H	PhN_2BF_4 + $CuCl_2$	$HN{=}C(SPh)NH_2 \cdot$ Picr (27); $H_2N{-}C(=NH){-}S{-}C(=NH){-}NH_2 \cdot 2$ Picr (2)	40
2	H	H	PAT	$HN{=}C(SPh)NH_2 \cdot$ Picr (1); $H_2N{-}C(=NH){-}S{-}C(=NH){-}NH_2 \cdot 2$ Picr (44)	41 42
3	Ph	Ph	PAT	$PhN{=}C(SPh)NHPh \cdot$ Picr (27)	43
4	Ph	Ph	NAA	$PhN{=}C(SPh)NHPh \cdot$ Picr (56)	43
5	H	Ph	PhN_2BF_4 + $CuCl_2$	$PhN{=}C(SPh)NH_2 \cdot$ Picr (60)	40

[a] In water

A comparison of Tables V and VI shows that introduction of substituents into thiourea greatly increases the yield of *S*-arylisothiouronium derivatives.

It should be noted that thiosemicarbazide and acetone thiosemicarbazone can be arylated with *p*-nitrophenyldiazonium tetrafluoroborate in the absence of copper salt (Table VI, Nos. 2, 4).[27] The radical character of this reaction has been proven by ESR[27] (see also Section V.1).

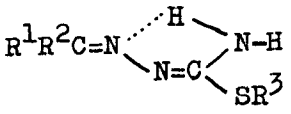
The data in Tables V–VII illustrate that arylation of thiourea and its derivatives with aryldiazonium salts can be used not only for studying the mechanism of these reactions, but also for the preparative synthesis of *S*-arylisothiouronium salts.

In the above-mentioned papers on the arylation of monosubstituted thioureas the structures of the *S*-phenylisothiouronium compounds formed in the reactions was reported without special regard to possible tautomeric transformations according to the Scheme:

$$\underset{\underline{1}}{RHN{-}C(=NH){-}SAr} \rightleftharpoons \underset{\underline{2}}{RN{=}C(-NH_2){-}SAr} \qquad (11)$$

For some cases the most probable structure may, apparently, be assumed. For instance, when R=Ph structure **2**, in which a double bond has become conjugated with an aromatic ring, is more probable.

It has been shown using IR and NMR spectroscopy[45] that *S*-methyl- and *S*-benzylisothiosemicarbazones have an NH_2 group and exist in the *cis*-conformation:



which favors the formation of an intramolecular hydrogen bond.[44] Therefore, we ascribe an amide structure **2** rather than an imide one to the *S*-phenylisothiosemicarbazides and -carbazones obtained by us.

II.4. Some Features of the Application of Aryl Radicals for the Arylation of the Thiocarbonyl Group

II.4.1. Thioamides The *S*-arylisothioamides formed by arylation of thioamides containing aryl substituents at a CS and/or NH group are thermally rather stable and the reaction can be carried out either at room temperature (with NAA) for 20 hours or at 60–65 °C (with PAT) for 10 hours. Acetone is the best solvent for the reaction. To follow the reaction course, it is convenient to take samples for thin-layer chromatography (on Silufol). The R_f values of the thioamides under study (0.3–0.6) are, as a rule, much lower than those of the *S*-arylisothioamides formed (0.5–0.8). The latter are readily isolated from the reaction mixture by either column chromatography on silica gel or by crystallization from alcohol.

II.4.2. Thioureas and Related Compounds The relatively high water solubility of thiourea makes it possible to carry out arylations in aqueous solution. Substituted thioureas are arylated more efficiently in aqueous acetone. The reaction temperature must not exceed 40–60 °C; the reaction time is 1–6 hours. Aryldiazonium tetrafluoroborates with 5 mol-% of $CuCl_2 \cdot 2\,H_2O$ are the best arylating agents for these compounds. The reaction products were isolated from the complex reaction mixtures, as a rule, by conversion to insoluble picrates after addition of a saturated aqueous alcoholic solution of picric acid. The picrates are readily purified by recrystallization from alcohol.

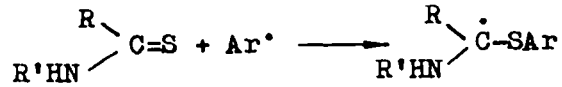
The structure of the compounds obtained was proven either by independent syntheses or by IR, ^1H and ^{13}C NMR, and mass spectra.

III. INTERMEDIATE RADICALS FORMED IN THE REACTIONS OF THIOCARBONYL COMPOUNDS WITH ARYL RADICALS AND THE PATHWAYS OF THEIR STABILIZATION. THE REACTION MECHANISM

The arylation of thioamides, thioureas, and related compounds described in the previous sections proceeds, undoubtedly, by a radical mechanism which was proven by the formation of radicals upon decomposition of the arylating agents being used.

III.1. Adduct Radicals

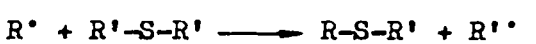
The fact that in all examples the aryl radicals are added to a sulfur atom gives grounds to believe that this reaction proceeds via an intermediate adduct radical **3**:



(12)

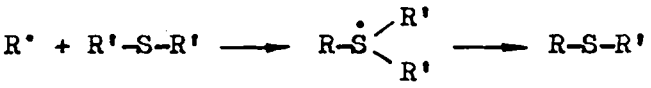
3

Radical **3** is, apparently, in some respect similar to the intermediate radicals formed in radical reactions of sulfides and disulfides. In some papers[3,45] the reaction of radicals with sulfides and disulfides, which formally is a substitution reaction:



(13)

is considered as an addition-abstraction reaction with intermediate formation of a "nonet" sulfuranyl radical **4**:

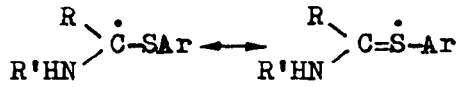


(14)

4

In some cases when R and R′ are strongly electron-attracting groups the formation of radicals **4** could be confirmed by ESR.[46–49]

One may assume that the adduct radicals **3** are also specific "nonet" radicals containing, as opposed to radicals **4**, dicoordinated, rather than tricoordinated, sulfur, i.e.

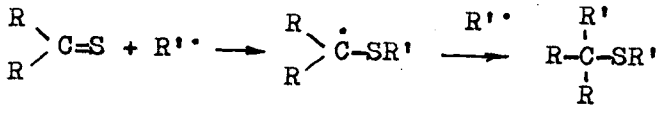


The formation of the radicals **3** has repeatedly been suggested as the reason for the stabilizing effect of thiyl group on a neighboring radical center.[50]

In the arylation of thioamides and thioureas it is often possible to follow further transformations of the intermediate radicals **3**.

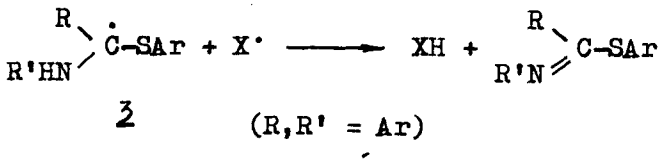
III.2. Cross-Disproportionation of Adduct Radicals due to Hydrogen Abstraction from NHR Groups

As is seen from Table III, the corresponding *S*-phenylisothioamides are almost the only products of the radical phenylation of aromatic thioamides. The absence of other reaction products indicates that an intermediate adduct radical **3** in these cases neither abstracts hydrogen from the solvent molecules nor is subjected to dimerization or cross-recombination with other radicals (for instance, phenyl) as in the reaction of thioketones with some radicals:[51]



(15)

Thus, the only route of transformation of the radicals **3** formed in the arylation of aromatic thioamides is, evidently, their cross-disproportionation with other radicals yielding isothioamides:



(16)

Scheme 16 implies the interaction of radical **3** with radical **X** which can abstract hydrogen. It is natural to assume that the role of **X** is played by one of the radicals formed in the course of decomposition of the radical forming agent. Since thermolysis of PAT produces, along with phenyl radicals, only relatively unreactive triphenylmethyl radicals (Scheme 1), one might expect that transformation of a thioamide into an *S*-phenylisothioamide will require 2 moles of PAT per mole of thioamide, i.e. the role of **X** participating in the cross-disproportionation with the radicals **3** (Scheme 16) is also played by phenyl radicals. Therefore, introduction of PAT in amounts less than 2 moles per mole of thioamide must decrease the yield of isothioamide. Indeed, it has been shown for some reactions[32] that a decrease of the PAT: thioamide molar ratio from 2:1 to 1:1 almost halves the yield; a part of the starting thioamide in this case remains unchanged so that the yield of isothioamide calculated for the amount of thioamide consumed is close to quantitative. This confirms the assumption that the hydrogen abstraction from the adduct radicals **3** in phenylations with PAT is performed by phenyl radicals.

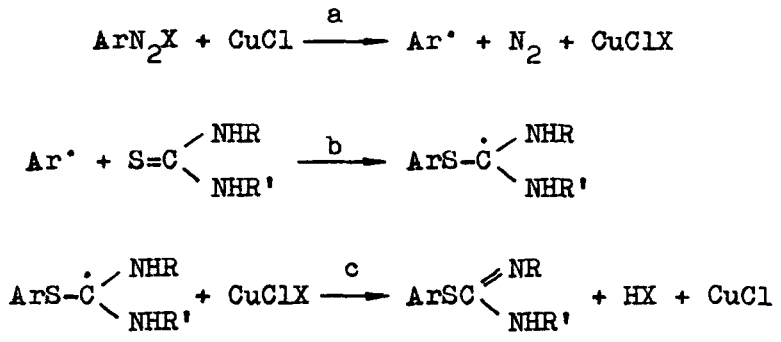
The situation is quite different when the phenylation is performed with NAA. A decrease in the NAA: thioamide molar ratio from 2:1 to 1:1 almost does not lower the yield of isothioamide.[32] This may be due to the fact that decomposition of 1 NAA molecule gives not only phenyl, but other radicals as well which are able to abstract hydrogen from the intermediate adduct radical.

The above considerations are, evidently, valid for arylation of thiourea and its derivatives by PAT and NAA in the cases where the corresponding *S*-phenylisothiouronium compounds are the reaction products.

It should be noted that in all the above reactions the same trend is observed: thioamides and thioureas containing an NH_2 group are arylated in much lower yields than their *N*-substituted analogs. This may be due the fact that abstraction of hydrogen from an NHR group of the adduct radical proceeds more readily than from an unsubstituted amino group.

III.3. Oxidation of Adduct Radicals with Cu^{II}

The formation of *S*-arylisothiouronium compounds in the radical arylation of thioureas with arydiazonium salts in the presence of copper chloride can be described by Scheme 17:



Scheme 17

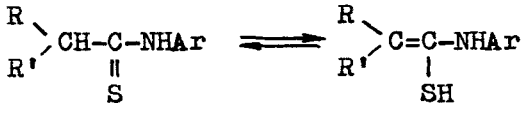
The aryl radicals are added to the sulfur atom but, contrary to the reactions with PAT or NAA, the abstraction of the hydrogen atom from the NHR group of the adduct radical is, apparently, taking place via its oxidation by divalent copper. Indeed, according to the scheme, the reaction requires only catalytic amounts of copper salt (up to 5 mol-%). The yield of isothiouronium compounds reaches twelve and more moles per mole of $CuCl_2$. This is in keeping with oxidation of Cu^{I} to Cu^{II} at stage "a" and reduction of Cu^{II} to Cu^{I} at stage "c". It should be noted that stage "c" is quite similar to the known oxidation reaction of alkyl radicals[52] with divalent copper salts which produces alkenes by the reaction:

(18)

III.4. Cross-Disproportionation of Adduct Radicals Due to Hydrogen Abstraction from CH Groups. Arylation of Diphenylthioacetic Acid Amides

In the above-mentioned reactions the stabilization of the adduct radical **3** is achieved by hydrogen abstraction from the NHR group adjacent to the radical center (Scheme 16). It was of interest to study the direction of cross-disproportionation in those cases where the adduct radical contains other groups which can be subjected to a homolytic attack involving hydrogen abstraction. For this purpose phenylation of diphenylacetic acid *N*-phenyl- (**5**) and *N,N'*-diethylamide (**6**) has been studied.[53]

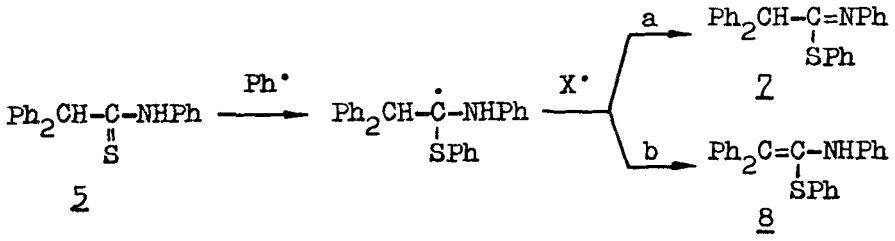
It was, however, necessary to establish the structure of these compounds since thioamides containing the $R_2CH—CS$ fragment (where R and R' are electron-withdrawing groups) can exist in a tautomeric enethiol form.



It has been shown on the basis of the IR spectra that when R=CN and R'=COOR the equilibrium is completely shifted to the enethiol form.[54,55]

The study of **5** and **6** by IR and NMR spectroscopy has shown that they have a thione structure both in the solid state and in solution.[53]

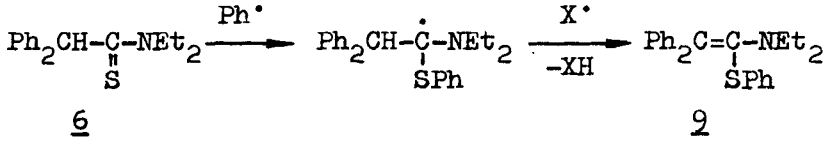
Phenylation of thioamide **5** may, in principle, proceed in two directions, involving the fragments S=C—NH or S=C—CH:



(19)

In practice, however, it turned out that only one arylation product, namely, the *S*-phenylisothioamide **7**, is formed in high yield; the structure of **7** was unambiguously proven by NMR, IR, and mass spectra.[53] It is known that *S*-substituted isothioamides can be in equilibrium with the corresponding ketene *N*,*S*-acetals **7** $\rightleftarrows$ **8**; in the case of other derivatives of diphenylthioacetic acid the equilibrium is almost completely shifted to the isothioamide form.[56] Thus, in this particular reaction the initial quantitative or partial formation of product **8** (stage "b" in Scheme 19) with further rapid isomerization to **7** could not be excluded.

Such a possibility is excluded in the arylation of tertiary thioamides. It has been shown for the reaction of thioamide **6** with NAA and PAT that in this case diphenylketene *S*-phenyl-*N*,*N*'-diacetal **9** is obtained in high yield:

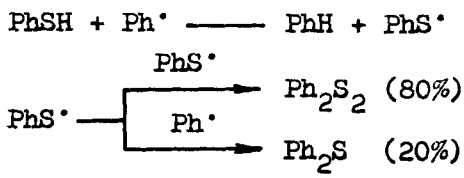


(20)

Its structure was also unambiguously proven by NMR and mass spectroscopy.[53]

Thus, the cross-disproportionation of the intermediate radicals formed in the arylation of thioamides proceeds not only with involvement of NH hydrogen, but also of CH hydrogen (Scheme 19). The latter route is, apparently, realized when hydrogen abstraction is facilitated by the presence of two aryl substituents: arylation of thioisobutyric acid *N*,*N*-diethylamide $(CH_3)_2CH—CS—NEt_2$ gives diphenyl disulfide rather than dimethylketene acetal.[18]

It is noteworthy that the high yield of *S*-phenylisothioamide and, correspondingly, of *N*,*S*-substituted diphenylketene acetal in the arylation of the thioamides **5** and **6** is another compelling proof of their thione structure since it has been shown that the main reaction product upon arylation of compounds with an SH group is the disulfide rather than the corresponding sulfide. For instance, interaction of thiophenol with NAA yields only 20 % of disphenyl sulfide and 80 % of diphenyl disulfide. Evidently, in this case the reaction proceeds via the hydrogen abstraction which gives a phenylthiyl radical. The latter mainly dimerizes and only partially recombines with a phenyl radical:



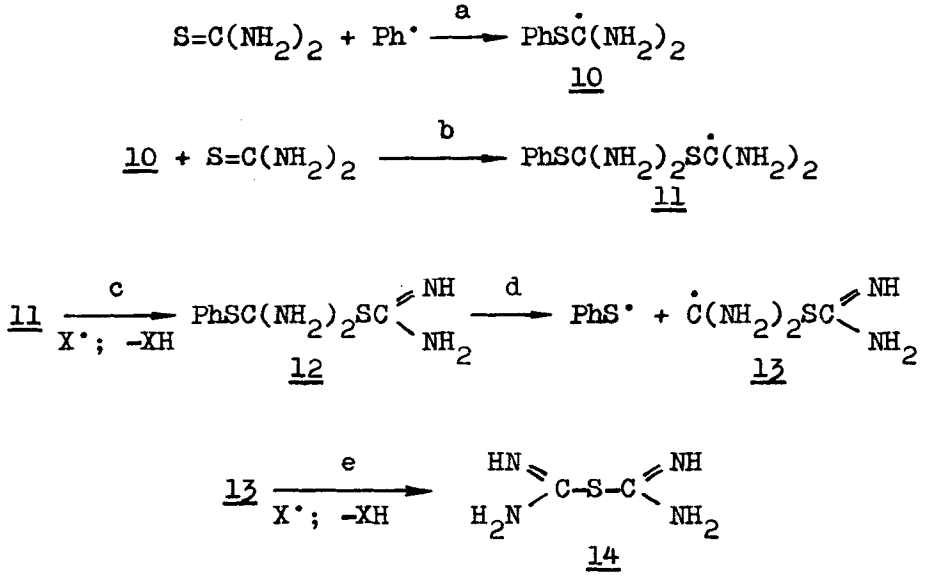
(21)

A relatively high yield of Ph_2S (up to 40–50 %) can be obtained only when the phenylating agent is used in great excess.† (Unpublished observations by the authors).

III.5. Stabilization of Adduct Radicals Involving the "Radical Growth" Stage

III.5.1. Formation of Bis-Formamidine Sulfide It has already been mentioned that the arylation of thiourea with different agents yields the title compound as a side or main product (see Table VII, Nos. 1, 2). The structure of this compound was proven by independent synthesis,[57] by the identity of the melting points of its salts with those known from the literature,[58] and also by ^{13}C NMR (the singlet resonance at δ = 161 ppm).

The formation of this compound in the reaction considered can be described by a scheme which includes the "growth" of the intermediate adduct radical.



Scheme 22

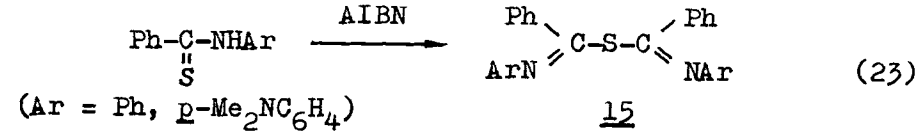
According to the scheme the adduct radical **10** formed in stage "a" adds to a second thiourea molecule ("growth" stage "b") giving rise to a "telomeric" radical **11** with two "monometric units". This radical is stabilized by disproportionation affording the intermediate compound **12** containing a hindered fragment with a carbon atom linked to

† In this reaction acetanilide is formed in a small yield (up to 3 %). This probably indicates that oxidation of thiophenol by NAA also occurs to a small extent (cf. Scheme 4).

two sulfide and two amino groups. That is why the compound **12** or the radical **11** eliminate PhS radicals (which dimerize to diphenyl disulfide) finally, giving rise to compound **14**.

It seems that the transformation of an adduct radical as shown in Scheme 22 is likely to occur when hydrogen abstraction from the radical is for some reasons complicated. Particularly, a facile hydrogen abstraction from an NHPh group as compared to that from an unsubstituted NH_2 group results in the formation of the corresponding isothiouronium compound in the analogous reaction with *N*-phenyl substituted thioureas (see Table VII, Nos. 3–5).

III.5.2. Formation of Bis-Imidosulfides in Reactions of Thioamides with AIBN The reaction of some thioamides with AIBN in benzene or toluene at 80–100 °C gives the bis-imidosulfides **15** in low yields:

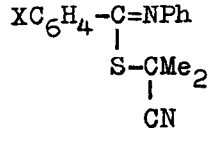


(23)

The formation of these compounds is probably due to a reaction sequence similar to that illustrated by Scheme 22. Such a course of the reaction may be due to the fact that the 2-cyanopropyl radicals formed in the AIBN thermolysis are, as is known, much less effective hydrogen abstractors than, for instance, phenyl radicals.[59] According to the above considerations, this must favor the "growth" of the initially formed adduct radical. Further transformations of a "telomeric" radical result in the stable bis-imidosulfide **15** via a reaction similar to (22).

The participation of the 2-cyanopropyl radicals in this reaction is supported by the fact that the reaction does not take place in the absence of AIBN or upon its replacement with other nitriles unable to form radicals.

Besides, it has been shown in the reactions of the thioamides $XC_6H_4CS—NHC_6H_5$ (X=*p*-NO_2, *p*-CH_3O) with AIBN that the imidosulfides **16** are formed in low yield. The structure of these compounds has been proven mass spectrometrically. Therefore, it is



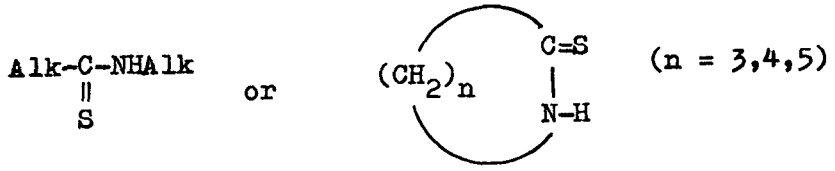
16

beyond doubt that this reaction differs from the known transformation of thiobenzanilide to benzanilide sulphide (**15**, Ar=Ph) which proceeds only in the presence of such condensing agents as S_2Cl_2, $SOCl_2$, SO_2Cl_2, $PhSO_2Cl$, and the like.[60]

It is noteworthy that the above "growth" of intermediate radicals is the first example of reactions of such a type having no analogies in the chemistry of thiocarbonyl compounds.

IV. RADICAL ARYLATION OF THIOAMIDES AND THIOUREAS CONTAINING UNSATURATED SUBSTITUENTS (DEPENDENCE OF THE REACTION PATHWAY ON THE CHARACTER OF THE THIOCARBONYL COMPOUND)

As mentioned phenylation of a number of thioamides, in particular,

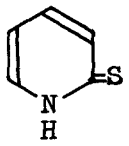


(see Table IV) yields diphenyl disulfide as the main sulfur-containing reaction product. This may be due to the fact that the adduct radical **17** formed in this case differs in its stability and reactivity from the radical **3** formed by arylation of aromatic thioamides:

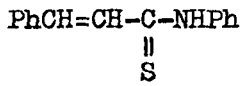
17 **3**

On one hand, **17** is less stable (since there is no stabilizing effect of an α-aryl group); on the other hand, abstraction of hydrogen from the NHAlk group in radical **17** proceeds with greater difficulty than in radical **3** where this hydrogen atom occupies a "quasi-benzylic" position. Therefore, the radicals **17** predominantly fragment and do not participate in cross-disproportionation or "growth" processes.

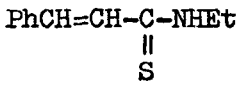
The study of the effect of unsaturated substituents in thioamides and thioureas on radical arylation was carried out for the following compounds:



18



19



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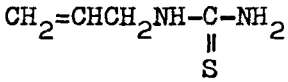

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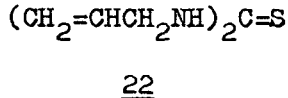


22

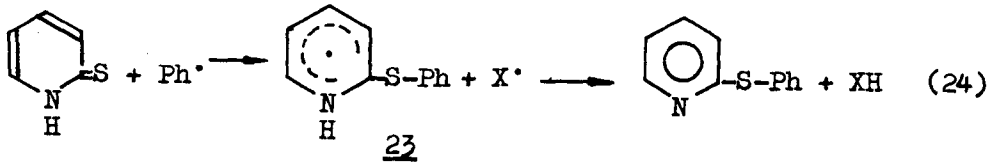
The reaction products and their yields are listed in Table VIII.

Three factors which favor the formation of the corresponding isothioamides (and isothiouronium compounds) are especially pronounced in the arylation of compounds **18–22**: the relative stability of the intermediate adduct radical, facile homolytic cleavage of the N—H bond, and sufficient stability of the end product.

IV.1. 2-Thiopyridone

2-Thiopyridone **18** is arylated smoothly by PAT with the formation of phenyl 2-pyridyl sulfide[18] (Table VIII, No. 1). In contrast to the unfavorable arylation of cyclic

thioamides (Table IV, Nos. 10–12), such a smooth reaction may be due to the fact that first, the adduct radical **23** formed (Scheme 24) is stabilized by conjugation of the radical center with a heterocyclodienyl system and, second, the hydrogen abstraction from the N—H group in the cross-disproportionation is facilitated by the formation of a heteroaromatic structure:

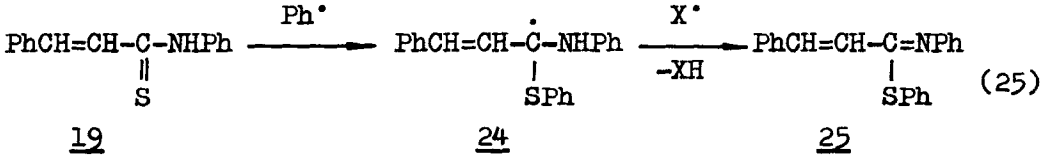


(24)

23

IV.2. Thiocinnamic Acid Amides

Phenylation of thiocinnamic acid anilide **19** by NAA proceeds readily without complications (Table VIII, No. 2) and leads to the isothioamide **25** in high yield.[61]

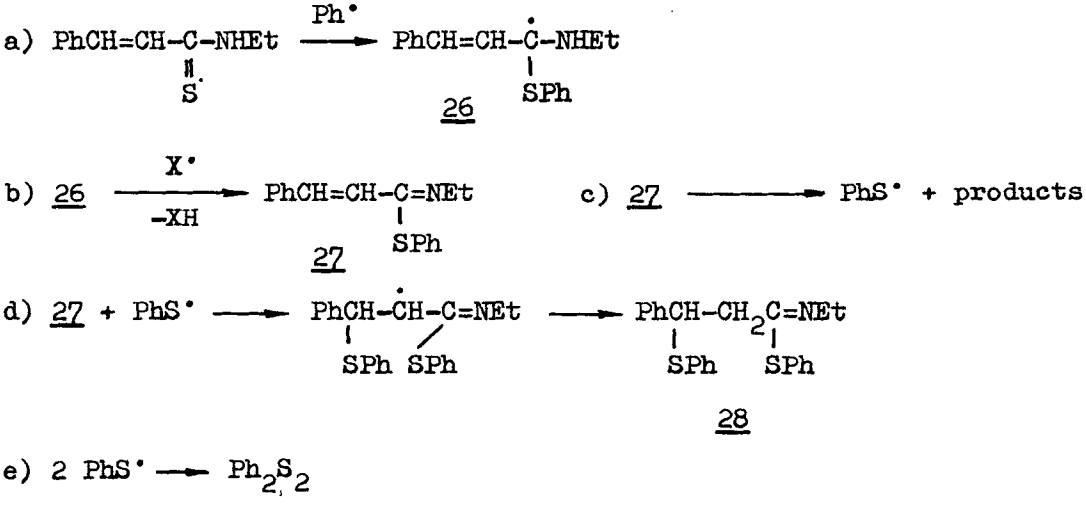


(25)

19 24 25

All three factors mentioned above are fully operative in this case, i.e. the adduct radical **24** is stabilized by an α-styryl substituent, the hydrogen abstraction from the NH group proceeds with ease, and the final product is stable.

More complicated is the reaction of thiocinnamic acid *N*-ethylamide **20** with NAA. A mixture of products is formed (Table VIII, No. 3); the reaction is described by the scheme:



Scheme 26

The ordinary reaction course is made impossible by the instability of the isothioamide **27** which decomposes even at room temperature with elimination of PhS· radicals. The

TABLE VIII

Radical Arylation of Thioamides and Thioureas Containing Unsaturated Substituents

No.	Thioamide/Thiourea	Source of aryl radicals	Reaction products (yield in %)	Ref
1	2-Thiopyridone	PAT	Phenyl 2-pyridyl sulfide (85)	18
2	PhCH=CH—CS—NHPh	NAA	PhCH=CH—C(SPh)=NPh (80)	61
3	PhCH=CH—CS—NHEt	NAA	PhCH(SPh)—CH_2—C(SPh)=NEt PhCH=CH—C(SPh)=NEt (65) Ph_2S_2 (10)	61
4	CH_2=$CHCH_2$NH—CS—NH_2	PhN_2BF_4 + $CuCl_2$	C_3H_5N=C(SPh)NH_2 (68)[a]	26
5	CH_2=$CHCH_2$NH—CS—NH_2	*p*-$NO_2C_6H_4BF_4$ + $CuCl_2$	C_3H_5N=C(—NH_2)—$SC_6H_4NO_2$-*p* (93)[a]	26
6	$(CH_2$=$CHCH_2NH)_2$C=S	PhN_2BF_4 + $CuCl_2$	C_3H_5N=C(SPh)NHC_3H_5 (60)[a]	26
7	$(CH_2$=$CHCH_2NH)_2$C=S	*p*-$NO_2C_6H_4N_2BF_4$ + $CuCl_2$	C_3H_5N=C(—NHC_3H_5)—$SC_6H_4NO_2$-*p* (67)[a]	26

[a] Isolated as a picrate

radicals recombine, giving diphenyl disulfide and add to **27** which leads to the formation of the stable bis-(phenylthio) derivative **28**. The formation of diphenyl disulfide confirms the intermediate formation of PhS· radicals. It has also been shown that in the presence of AIBN thiophenol adds readily to **25** yielding the bis-(phenylthio) derivative **29**:

$$\underset{\underline{25}}{PhSH + PhCH{=}CH{-}C(SPh){=}NPh} \xrightarrow{AIBN} \underset{\underline{29}}{PhCH(SPh){-}CH_2C(SPh){=}NPh} \qquad (27)$$

which confirms the involvement of a similar reaction (stage "d" in Scheme 26).

IV.3. Allyl- and Diallylthioureas

N-Allyl and *N,N'*-diallylthioureas (Table VIII, Nos. 4–7) are arylated by aryldiazonium tetrafluoroborates in the presence of $CuCl_2$ with formation of the corresponding isothiouronium compounds in high yield (isolated as picrates).[28]

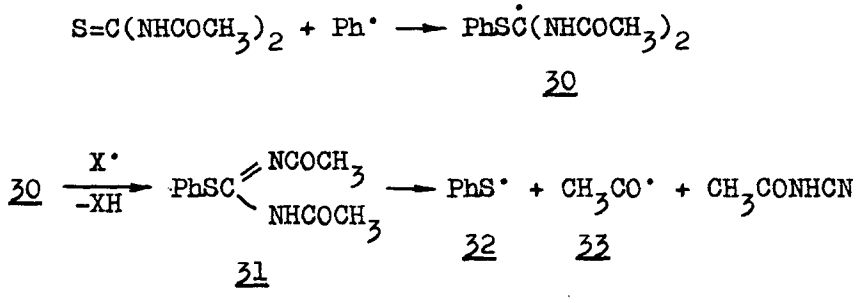
V. INTERACTION OF THIOUREAS CONTAINING ELECTRON-WITHDRAWING GROUPS WITH NAA

In contrast to thiourea and its *N*-phenyl and *N*-allyl derivatives, as well as thiosemicarbazide and acetone thiosemicarbazone (Tables V–VIII), interaction of *N,N'*-diacetylthiourea with NAA did not give the corresponding *S*-phenylisothiouronium

compound.[62,63] Among the reaction products, however, are some compounds which contain PhS groups: Ph_2S_2, CH_3COSPh, and $(PhS)_2C(NHCOCH_3)_2$ (Table IX). The formation of these compounds suggests that in this case the addition of phenyl radicals to the sulfur atom of *N,N'*-diacetylthiourea has also occurred. The accumulation of electron-withdrawing acetyl groups in a molecule, however, destabilizes the intermediate products to such an extent that they decompose even at room temperature.

V.1. The Reaction Between N,N'-Diacetylthiourea and Phenyl Radicals as Studied by ESR

The mechanism of decomposition of isothiouronium compounds has not been studied yet, although their instability is well known.[64] This prompted us to study the reaction in detail by the ESR method.[63] Upon phenylation of *N,N'*-diacetylthiourea with phenyl radicals, generated by oxidation of 1-phenyl-3-*t*-butyl-3-oxytriazene with PbO_2,[65] the ESR spectrum was found to consist of three triplets with a_N 16.6, 8.1, and 15.3 G, respectively.[63] According to the literature data, [66,67] the first and second triplets correspond to the spin adducts of PhS· and CH_3CO· radicals. The third triplet is assigned presumably[63] to a spin adduct of $PhS\dot{C}(NHCOCH_3)_2$ **30**. On the basis of these data the reaction in question can be represented by the following scheme:



Scheme 28

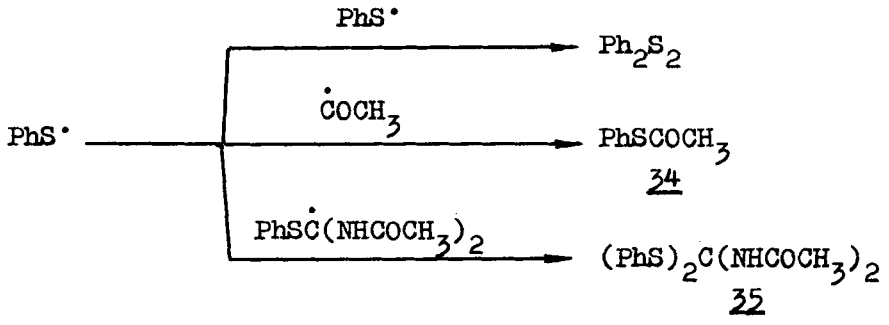
Identification and preparative isolation of the reaction products (Table IX) made it possible to elucidate the further fate of the radicals **30**, **32**, and **33**.

TABLE IX

Reaction of *N,N'*-Acetylthiourea with NAA[63]

Reaction products	Yield in %
Ph_2S_2	50
$PhSCOCH_3$	20
$(PhS)_2C(NHCOCH_3)_2$	16
$CH_3CONH—CO—NH_2$	15
$(CH_3CONHCN)_2$	10
Acetylcyanamide polymers	

The phenylthiyl radicals **32** dimerize and cross-recombine with the radicals **30** and **33**:



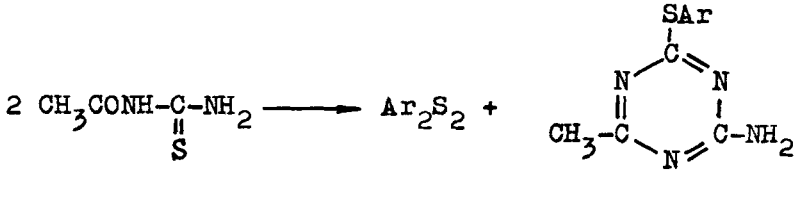
Scheme 29

The formation of **35** is experimental evidence for the intermediate formation of the adduct radical **30** via Scheme 28. The validity of the scheme is also confirmed by the formation of a dimer and polymers of acetylcyanamide and the product of its hydrolysis (*N*-acetylurea)[63] (Table IX). It is seen from the Table that the total yield of the products of *S*-phenyl-*N*,*N*′-diacetylisothiourea decomposition is close to quantitative. It should be noted that the same intermediate radicals and products can be formed not only from the isothiourea **31** but also directly from radical **30**.

Apparently, the decomposition of unstable isothioamides containing *N*-acetyl substituents atom (for instance, *S*-benzyl-*N*-acetylisothioamide[56]) may follow similar schemes.

V.2. Reactions of N-Acetylthiourea with NAA and NAT

Attempts to prepare the corresponding *S*-arylisothiouronium compounds by reaction of *N*-acetylthiourea with NAA or NAT were unsuccessful.[62] In this case, however, contrary to a similar reaction with *N*,*N*′-diacetylthiourea, substituted *s*-triazines are formed according to the scheme:



(30)

(Ar = Ph, *p*-$CH_3C_6H_4$)

The yields of the compounds obtained are given in Table X (Nos. 1, 2).

As is seen from Table X, the reactions furnish compounds containing ArS-group in high yields. The formation of diaryl disulfides is indicative of a partial decomposition of **37**. Unlike the reaction between *N*,*N*′-diacetylthiourea and NAA, a considerable part of **37** reacts with the radicals formed. The formation of the triazines **36** in this process can be

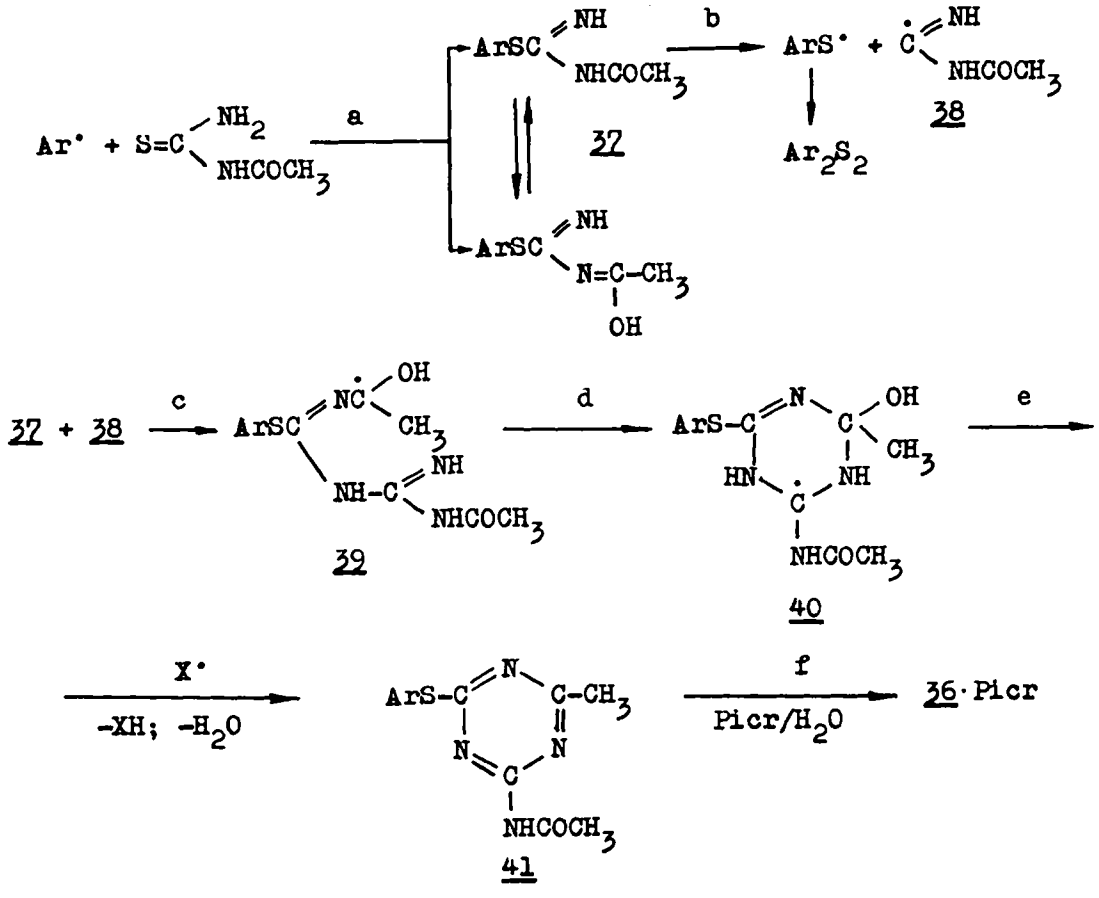
TABLE X

Arylation of Acetyl Substituted Thioureas $CH_3CONH—CS—NHR$[62]

No.	R	Ar (aryl source)	Reaction products, yields in %	
			Ar_2S_2	*36*[a]
1	H	Ph (NAA)	35	40
2	H	*p*-$CH_3C_6H_4$ (NAT)	23	36
3	CH_3CO	*p*-$CH_3C_6H_4$ (NAT)	28	10

[a] Isolated as picrates

illustrated by Scheme 31 which involves a consecutive transformation of the radicals **38**, **39**, and **40**:



Scheme 31

Such "cascade" transformations of active intermediates often take place in various organic reactions.[68]

Scheme 31 assumes an initial formation of *S*-aryl-*N*-acetylisothiourea **37** (stage "a"), its decomposition (stage "b") similar to that of *S*-phenyl-*N,N'*-diacetylthioisothiourea (see Scheme 28), and addition of the radicals **38** to a second molecule of **37** with formation of the radicals **39** (stage "c"). Cyclization of the radicals **39** to **40** (stage "d") and cross-disproportionation of **40** with other radicals produce the substituted arylthio-*s*-triazines **41**. During the formation of the corresponding picrates by treatment with aqueous alcoholic picric acid **41** form **36** due to hydrolysis of the acetylamino group. The alternative mechanism of the formation of products **41** and **36** by the conventional heterolytic condensation of *N*-acetylthiourea with **37** cannot be excluded, but compound **37** is undoubtedly formed by a radical mechanism.

It is interesting that *N,N'*-diacetylthiourea reacts with NAT in a somewhat different way than with NAA. In the reaction with NAT decomposition of an intermediate isothiouronium compound is incomplete which may be due to the electron-withdrawing effect of the p-$CH_3C_6H_4$ group; as a result, the corresponding triazine is obtained in low yield (Table X, No. 3).

The structure of the heterocyclic compounds synthesized has been proven by ^{13}C NMR and IR spectroscopy.[62]

VI. FRAGMENTATIONS AND REARRANGEMENTS OF AROMATIC THIOAMIDES UNDER ELECTRON IMPACT

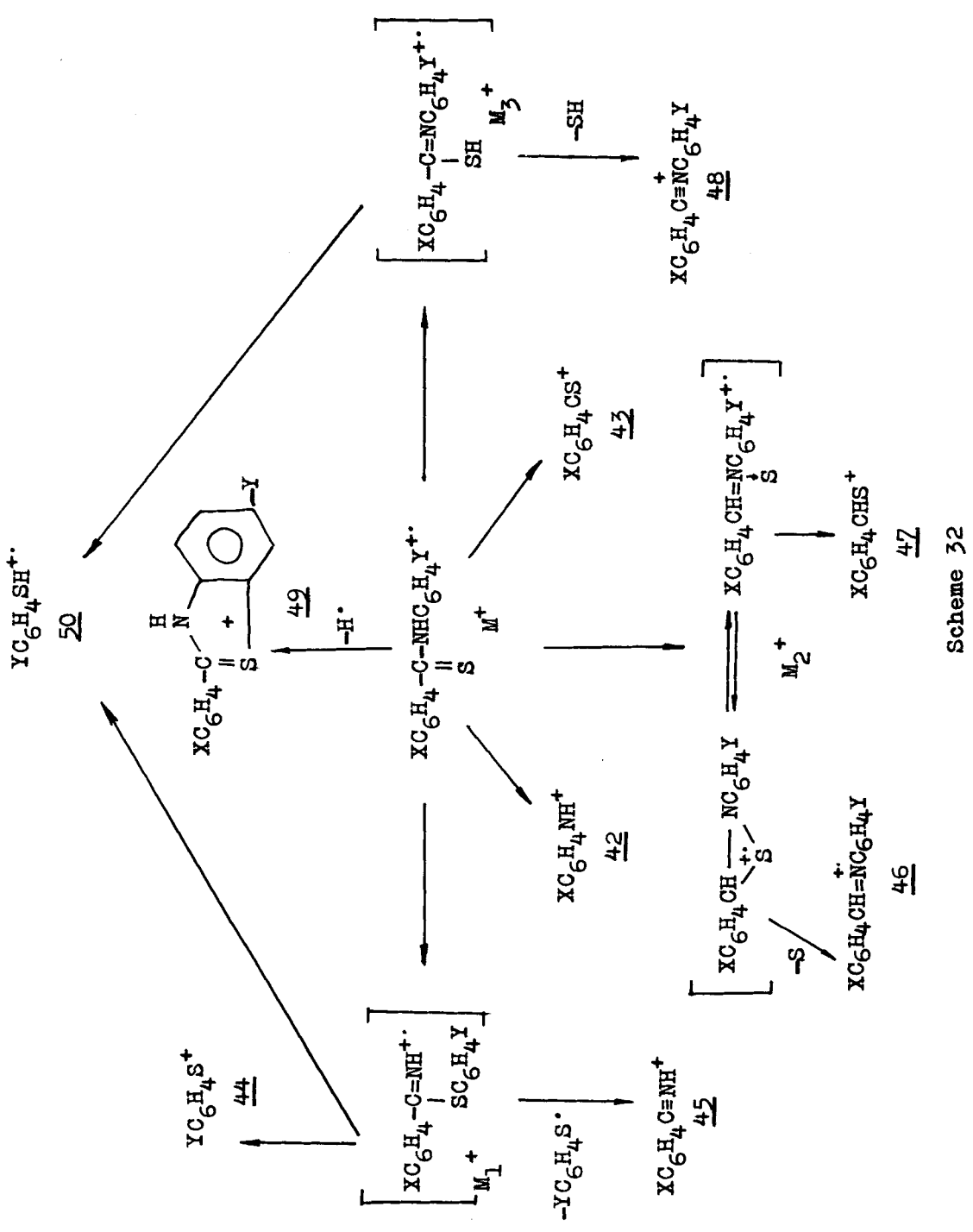
Gas-phase intramolecular transformations of radicals and ion radicals induced by electron impact occupy a unique position among radical reactions. The study of these processes for such polyfunctional compounds as thioamides and thioureas is very promising for the elucidation of the reactivity of some functional fragments in these compounds.

The mass spectrometric behavior of thioamides is the subject of several papers published recently.[69-74] The main fragmentation patterns of aromatic thioamides were established in studies of the mass spectra of thiobenzanilides:

$$XC_6H_4—CS—NR\text{-}C_6H_4Y \text{ where R is } CH_3^{72} \text{ or } H.^{72,74}$$

The decomposition of these compounds (Scheme 32) was shown to differ greatly from that of their oxygen analogs, the benzanilides, where the only fragmentation route consists of a cleavage of the amide bond with the formation of a benzoyl cation and products of its decomposition.[75]

Molecular ions of thiobenzanilides also dissociate at the C—N bond yielding **42** and **43** (Scheme 32) and their fragments. Besides, the mass spectra of all thiobenzanilides studied contain ion peaks the formation of which cannot be explained by fragmentation of the molecular ion M_1^+. Evidently they are formed from isomeric forms M_1^+, M_2^+, and M_3^+. Thus, the ions **44** and **45** are, apparently, fragments of M_1^+ formed from M^+ via migration of the aryl group from nitrogen to sulfur. Another type of M^+ isomerization, namely its closing to a thiazirane structure M_2^+ may be responsible for the formation of **46** and **47**. Such an assumption agrees with the known fact of the formation of benzaldehyde ion from an oxazirane ion via oxygen atom elimination.[76]



Scheme 32

As far as **48** is concerned, its formation can be explained by a preliminary isomerization of $M^{+\cdot}$ into a thiolimide form $M_3^{+\cdot}$ due to migration of a hydrogen atom from nitrogen to sulfur and subsequent elimination of a sulfhydryl group. Such a conclusion was made on the basis of low-voltage spectra and spectra of *N*-deutero analogs of some thiobenzanilides.[74] The isomerization of the molecular ions of thioamides into a thiolimide form unknown in the ground state was assumed previously to explain the formation of $(M-SH)^+$ ions in the mass spectra of thioformanilides.[69] It is noteworthy that, according to the data obtained for *N*-phenylthioureas, no such isomerization does, apparently, take place.[77]

The mass spectra of deuterated thiobenzanilides[74] have also shown that the process of the formation of the $(M-H)^+$ ion **49** does not involve the amide hydrogen. A similar conclusion was made for *N*-phenylthioureas.[77]

A study of the temperature dependence of the mass spectra of thioamides has shown that all the above isomeric transformations are induced by electron impact only and do not take place upon evaporation of the samples.[74]

Apparently, the isomerization of molecular ions of thiobenzanilides in different possible directions is responsible for the fact that for thiobenzanilides, unlike their oxygen analogs, no simple relationship is observed between the intensities of the ions of various fragments and the electronic effects of the substituents on the phenyl groups.

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