Contribution of Professor Charles Rees to the development of the chemistry of disulfur dichloride

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With gratitude to Professor Charles Rees from his students and co-workers

Abstract

Sulfur transfer reagents play an important role in organic synthesis, and sulfur chlorides, especially disulfur dichloride, are exceptional examples. Professor Charles Rees proposed novel strategies for preparing sulfur-nitrogen heterocycles from readily available organic substrates using disulfur dichloride. Together with his coworkers, he developed cascade transformations for synthesizing a wide range of heterocyclic systems, including 1,2-dithioles, 1,2,3,4,5-pentathiepins, 1,2,3-dithiazoles, 1,2,5-thiadiazoles, 1,4-thiazines, and 1,2,3,4,5,6,7-heptathiocanes. This review highlights Professor Rees’s contributions to the chemistry of disulfur dichloride.

Keywords: Disulfur dichloride, heterocycles, one-pot synthesis, 1,2-dithioles, 1,2,3-dithiazoles, 1,2,3,4,5-pentathiepins, tertiary amines, chalcogen exchange

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1. Introduction

Sulfur-nitrogen heterocycles are of considerable interest to both chemists and materials scientists, and interest in them has been growing for decades. The presence of heteroatoms leads to significant changes in cyclic molecular structures due to the lone pairs of electrons and the difference in electronegativity between sulfur and nitrogen and carbon. As a result, these unique heterocycles have a number of features in contrast to all-carbon-containing compounds, and have promising material properties in both the pharmaceuticals and agrochemical fields, as well as compounds with interesting physical properties in optoelectronics, magnetism, and electrical conductivity (see Section 6.6).

In a paper published in 1992, Professor Charles W. Rees (Imperial College, London, UK) recognized the importance and the great potential of sulfur-nitrogen heterocyclic chemistry for the development of new drugs and materials. One of the most common routes for the synthesis of sulfur-nitrogen-containing heterocycles is the reaction of nitrogen-containing compounds with sulfur-containing reagents. One of the most effective and inexpensive such reagents is disulfur dichloride ($S_2Cl_2$). Professor Rees was one of the first to realize the key role of this reagent, and he introduced it into wide practice. It took Rees and his colleagues many years to understand the main advantages and disadvantages of this reagent.

In the course of this research, Rees and his colleagues found that disulfur dichloride is highly reactive to a variety of functional groups in organic compounds. This is because reactions with $S_2Cl_2$ formally lead to products of various chemical reactions, which have been reviewed in many publications. For example, $S_2Cl_2$ has been used for the perchlorination of aromatic compounds. Disulfur dichloride is also considered to be a reactive electrophile and an oxidizing agent. However, its sulfurizing ability is the most pronounced. All these reactivities of disulfur dichloride typically manifest themselves simultaneously, which reduces its value as a selective sulfur agent on the one hand but leads to complex cascade transformations with the formation of unusual heterocyclic compounds on the other hand.

Prior to Rees’s work, disulfur dichloride was typically used in reactions with organic compounds alone, without the addition of activating reagents. Rees’s contribution was to use bases, mainly organic, to activate...
transformations, which led to the discovery of a new theme in organic chemistry: the reaction of disulfur dichloride with nitrogen-containing bases.

2. Reaction of disulfur dichloride with oximes and related compounds

1,2,3-Dithiazoles are one of the most interesting classes among five-membered sulfur-nitrogen heterocycles because of their important physical and biological properties and versatile chemical composition. The abundance of monocyclic 1,2,3-dithiazoles can be explained by the easy availability and high and varied reactivity of 4,5-dichloro-1,2,3-dithiazolium chloride, also known as Appel salt. Remarkably, apart from Appel salt, only a few 4-substituted 1,2,3-dithiazolium chlorides have been isolated in free form (see Section 6.3).

The possibility of synthesizing 4-substituted 5-chloro-1,2,3-dithiazolium chlorides was demonstrated by reactions of acetophenone oxime and its 4-nitro derivative with $S_2Cl_2$ in the absence of any base (Scheme 1). The existence of these salts has been proven by reactions with aniline and water to form the corresponding imines and ketones.

![Scheme 1. Reaction of acetophenone oximes with $S_2Cl_2$.](image)

Similarly, 8-phenylindenodithiazole 2 was obtained by the reaction of a cyclic oxime 3 with disulfur dichloride in THF in 58% yield (Scheme 2).

![Scheme 2. Reaction of 3-phenyl-1H-inden-1-one oxime 3 with $S_2Cl_2$.](image)

Significantly, when this reaction was extended to the oximes of cyclopentenone and cyclopentanone, no dithiazole ring was formed. The most important condition for the formation of the dithiazole ring was the use of $N$-ethyl(diisopropylamine (Hünig’s base) as a reagent, resulting in the highest yields of dithiazoles 2 (90%) and 4 (25%) (Scheme 3). The yield of the final product of this complex multistage transformation strongly depends on the smallest changes in the reaction conditions, because the mechanism includes numerous reactions of chlorination, dehydrochlorination, and oxidation (according to the authors). If the carbocyclic ring is protected by a phenyl substituent (see formation of compound 2), chlorination of this ring does not occur.
Scheme 3. Synthesis of 4,5,6-trichlorocyclopenta[d][1,2,3]dithiazole.

The reaction proceeds similarly for the oxime of a seven-membered cyclic ketone, forming a mixture of chlorinated cyclohepta-1,2,3-dithiazoles 5 and 6 (Scheme 4). A 15-fold excess of disulfur dichloride is used for chlorination, and polychlorination occurs in higher yields with N-chlorosuccinimide (NCS).^{18}

Scheme 4. Reaction of cycloheptanone oxime with \( \text{S}_2\text{Cl}_2 \).

6\(H\)-1,2,3-Benzodithiazol-6-ones 7 were similarly synthesized from benzoquinone-4-oximes, \( \text{S}_2\text{Cl}_2 \), \( N \)-ethyldiisopropylamine, and NCS (Scheme 5). The formation of the dithiazole ring from the oxime is accompanied by chlorination, as usual. The substituents at positions -2 and -6 of the benzoquinone ring remain unchanged in the reaction products, except for the tert-butyl group, which is replaced by a chlorine atom. 1,4-Naphthoquinone-4-oxime and 1,2-naphthoquinone-2-oxime form dithiazoles 8 and 9 under the same conditions.^{19}

Scheme 5. Reaction of benzoquinone-4-oximes with \( \text{S}_2\text{Cl}_2 \).

Cyclopenta-1,2,3-dithiazolium system 10 is formed by reacting 2-substituted oximes of cyclopentanone and disulfur dichloride and Hünig’s base (Scheme 6).^{20} This reaction is accompanied by exhaustive
chlorination, as is the case with other cyclopentadithiazoles (see above). In selected examples, triisobutylamine can successfully replace the Hünig’s base.\textsuperscript{21}

\begin{center}
\begin{tikzpicture}
  \draw[fill=white] (0,0) circle (0.15cm);
  \node at (0,0) {S\textsubscript{2}Cl\textsubscript{2}, EtN(P\textsubscript{t})\textsubscript{2}};
  \draw (0,0) -- (1.5,0);
  \node at (2,0) {R = CH\textsubscript{2}CH\textsubscript{2}CN, CH\textsubscript{2}CH\textsubscript{2}CO\textsubscript{2}Et, CO\textsubscript{2}Et, CO\textsubscript{2}Me}.
\end{tikzpicture}
\end{center}

\textbf{Scheme 6.} Synthesis of cyclopet-1,2,3-dithiazoles 10.

The same approach was also used to prepare pentacyclic bis[1,2,3]dithiazolo-s-indacenes 11 and 12 from dioximes of 1,5- and 1,7-hydrindacenediones 13 and 14 in 46 and 75\% yields, respectively (Scheme 7).\textsuperscript{21} In the preparation of 11, the reaction is complicated by the hydrolysis of one oxime group, which leads to the formation of monodithiazole 15.

\begin{center}
\begin{tikzpicture}
  \draw[fill=white] (0,0) circle (0.15cm);
  \node at (0,0) {S\textsubscript{2}Cl\textsubscript{2}, Bu\textsubscript{3}N};
  \node at (1.5,0) {THF};
  \draw (0,0) -- (1.5,0.5);
  \node at (1.5,0.5) {13};
  \draw (1.5,0.5) -- (3,0);
  \node at (3,0) {11};
  \node at (3,-0.5) {15};
  \node at (3,-0.5) {15, 34\%};
  \node at (0,-0.5) {12};
  \node at (0,-0.5) {12, 75\%};
\end{tikzpicture}
\end{center}

\textbf{Scheme 7.} Reaction of dioximes of 1,5- and 1,7-hydrindacenediones 13 and 14 with S\textsubscript{2}Cl\textsubscript{2}.

\section*{3. Synthesis of other sulfur containing heterocycles}

Disulfur dichloride, in the presence of a chlorinating agent (NCS) and Hünig’s base, proved to be an effective sulfuration system for obtaining other heterocycles by reaction with various classes of compounds. The reactions of S\textsubscript{2}Cl\textsubscript{2} with NCS and Hünig’s base in THF with 1-cyclopentenylacetic acid, 3-indenylacetic acid, its nitrile, and 1-(dicyanomethylene)indane\textsuperscript{22} sometimes gave completely different types of heterocyclic and polychlorinated derivatives. The cyclopentenylacetic acid yielded trichlorocyclopenta-1,2-dithiole ester 16, the product of heterocyclic ring formation, chlorination, and dehydrochlorination, furthermore unexpectedly, conversion of the acid into its 4-chlorobutyl ester also occurred (Scheme 8).
Scheme 8. Reaction of cyclopentenylacetic acid with S$_2$Cl$_2$.

Treatment of 3-indenylacetic acid with S$_2$Cl$_2$, Hüning's base, and NCS in various solvents yielded three crystalline products (Scheme 9). The main reaction product (yield 32%) was polychlorinated methyleneindene 17, which did not contain sulfur atoms. It was likely formed as a result of intense chlorination and dehydrochlorination of indenylacetic acid, which is common in S$_2$Cl$_2$ reactions, as well as chlorine decarboxylation. The other two products, 18 and 19, were heterocyclic compounds containing sulfur atoms in the ring. The formation of heterocycle 18 is based on the ability of the S$_2$Cl$_2$ system, NCS, and Hüning's base, discovered by Professor Rees, to form 1,2-dithiole rings with activated allyl systems followed by extensive chlorination-dehydrochlorination to form completely unsaturated and chlorinated products. It is hypothesized that the acid group is lost by decarboxylation to form 3-chloro-1,2-dithiolium chloride, which then reacts with some external source of oxygen, as has been suggested in similar reactions. The formation of a condensed thiophenone 19 is rare in S$_2$Cl$_2$ reactions. It has been suggested that S$_2$Cl$_2$ converts carboxylic acids to acid chlorides, which can then be cyclized to a 1,2-dithiine derivative in this conversion. This derivative can eventually be converted into a thiophene by extrusion of the sulfur atom.

Scheme 9. Reaction of 3-indenylacetic acid with S$_2$Cl$_2$.

Dicyanomethyleneindane forms dichloroindene 20 and red thermochromic indeno-1,2-thiazine 21 under similar conditions (Scheme 10). The most probable pathway for the conversion of dicyanide to thiazine is shown in Scheme 10. The addition of S$_2$Cl$_2$ to the nitrile bond, followed by cyclization to the activated allyl
position, leads to dithiazepine 22. Standard chlorination-dehydrochlorination, followed by extrusion of sulfur, leads to a planar and formally aromatic product 21.

![Scheme 10. Reaction of dicyanomethylene indane with S₂Cl₂.](image)

Many of these products, when heated in a hot stage polarizing microscope, showed birefringence, indicating their liquid crystal behavior. This opens up a new class of discotic liquid crystals in which the molecular order of the mesophases is maintained by intermolecular interactions.²⁴

Cyclobutanone oxime 23, unlike other cyclic oximes, reacted with a mixture of S₂Cl₂, NCS and Hünig's base to form cyclopenta-1,2-thiazine 24. It also formed two other unexpected 10π pseudoazelenes, 25 and 26 (Scheme 11).²⁵ Treatment of oxime of the 27 also results in a mixture of products, mainly methylenoindene 28 and also the similar benzo product 29.²⁶ The simplest mechanism for the conversion of oxime 23 to 1,2-thiazine 24 may be an abnormal fragmentation of ketoxime (second order) according to Beckmann, induced by disulfur dichloride. This opens the cyclobutane ring to form nitrile 30, which adds S₂Cl₂ to form a 7-membered dithiazepine ring. A sequence of dehydrogenation and chlorination then gives completely chlorinated product 31. This is formally a 12π system, which subsequently loses sulfur to form a more stable 10π thiazine 24 (Scheme 11).
Scheme 11. Reaction of cyclobutanone oximes with $S_2Cl_2$.

4. Reaction of disulfur dichloride with tertiary amines

In the late 1990s, Charles Rees and co-workers unexpectedly found that disulfur dichloride reacted with practically all trialkylamines investigated. These studies began after the discovery that $N$-ethyldiisopropylamine (Hünig’s base), previously used as an "inert" base, reacts with disulfur dichloride and 1,4-diazabicyclo[2.2.2]octane (DABCO), unexpectedly forming a new multisulfur-nitrogen system, bis[1,2]dithiolo[1,4]thiazine 32. Remarkably, in this unique one-pot conversion of the Hünig’s base to tricycle 32, the 14 isopropyl CH bonds are replaced by 10 C-S bonds and two C=C double bonds, while the ethyl group remains intact. This reaction is a striking example of high selectivity between primary and secondary $N$-alkyl groups in a competitive reaction (Scheme 12).


It turned out that this unprecedented reaction between two reagents, Hünig’s base and disulfur dichloride, can lead to 16 compounds in one-pot transformations when various substances are added. Some of these compounds are formed selectively and with high yields (Scheme 13).
Scheme 13. Compounds obtained from the reaction of $S_2Cl_2$ and $N$-ethylidiosopropyl-amine.

Other bis[1,2]dithiolo[1,4]thiazines 33 and 34 were also selectively prepared by the reaction of Hünig's base with disulfur dichloride in the presence of oxygen donors, cyclopentadienylacetic or formic acids (Scheme 14).28


All tricyclic $N$-substituted bis-dithiolothiazines adopt a bent conformation but there is one exception to this molecular habit. The parent ring, having hydrogen on nitrogen, is a planar compound in the solid state. This compound 35 was obtained by debenzylation of the $N$-benzyl-substituted derivative of bis[1,2]dithiolo[1,4]thiazine (Scheme 15).29-30

The reaction of Hünig’s base with disulfur dichloride in refluxing chlorobenzene gave the corresponding bis[1,2]dithiolopyrroles 36–38 by the extrusion of a sulfur atom from thiazines 32–34 (Scheme 16).³¹


On further studying the reactions of substituted diisopropylamines with disulfur dichloride, Rees and colleagues synthesized a series of tricyclic bis-dithiolothiazines, including the parent members.²⁹,³²,³³ Treatment of N-(2-chloroethyl)diisopropylamine with disulfur dichloride in tetrahydrofuran, followed by the addition of phosphorus pentasulfide, led to the unexpected formation of the dithiolothiazine bicyclic system.³² The authors suggested that the formation of partially saturated thiazine 39 occurs by sulfuration of the chloroethyl group by $P_2S_5$ followed by addition to the dithiole ring (Scheme 17).

Scheme 17. Synthesis of 4-(3-thioxo-3H-1,2-dithiol-4-yl)-3H,4H-[1,2]dithio[3,4-b][1,4]thiazine-3-thione.
Treatment of N-ethyldiisopropylamine, \( S_2Cl_2 \), and DABCO in chloroform at room temperature followed by the addition of arenesulfonamides and their \( N,N \)-dichloro derivatives led to the formation of \( N,N' \)-bis(arylsulfonyl)dithiolothiazinediimines 40 in moderate yields (Scheme 18).\(^{34}\)

![Scheme 18. Synthesis of \( N,N' \)-bis(arylsulfonyl)dithiolothiazinediimines.](image)

The reaction of \( N \)-alkyldiisopropylamines with disulfur dichloride and a reduced amount of DABCO with respect to \( S_2Cl_2 \) prevented the formation of the 1,4-thiazine ring and led to the formation of \( N,N \)-bis(5-chloro-3-oxo[1,2]dithiol-4-yl)amines 41, although in low yields, by chlorination of intermediate dithiazolium salts with excess \( S_2Cl_2 \) and then conversion into keto derivatives by treatment with formic acid (Scheme 19).\(^{35}\)

![Scheme 19. Synthesis of \( N,N \)-bis(5-chloro-3-oxo[1,2]dithiol-4-yl)amines 41.](image)

In all the reactions discussed in this section, both isopropyl groups were converted into a 1,2-dithiole ring. When mixing \( N \)-alkyldiisopropylamines and disulfur dichloride in chloroform in the absence of another base, DABCO manages to carry out the reaction at one of the isopropyl groups and two monocyclic dithiole-3-thiones 42 and 43 result. In all cases considered, the main product was the 5-mercapto derivative 42 (Scheme 20).\(^{36,37}\)

![Scheme 20. Synthesis of monocyclic 1,2-dithioles from substituted diisopropylamines.](image)
Rees and co-workers showed that the reaction of disulfur dichloride with diisopropylamines can be stopped at the stage of formation of monocyclic 1,2-dithioles. The main condition for the successful synthesis of monodithioles is low temperature (-15 °C). In accordance with the previously proposed mechanism for the formation of a dithiole ring in these reactions, the combination of an excess of disulfur dichloride over a tertiary amine and DABCO led to the formation of a dichlorodithiole salt, which in the presence of an oxygen nucleophile (formic acid) gives 5-chlorodithiol-3-one 44 (Scheme 21). The synthesis of 1,2-dithiol-3-ones under unusually mild conditions is exceptional among the known corresponding methods and opened up new wide opportunities for studying this promising chemical class.

\[
\text{R} \quad \begin{array}{c}
\text{N} \\
\text{Cl}
\end{array}
\text{HCO}_2\text{H} \quad -15 ^\circ \text{C}
\]

**Scheme 21.** Synthesis of monocyclic 5-chloro-1,2-dithiol-3-ones 44.

Professor Rees' research has shown that an isopropyl group attached to a sulfur atom can also undergo similar transformations. Thus, the reaction of diisopropyl sulfide with disulfur dichloride and DABCO led to the formation of 1,2-dithiole-3-thiones 45 and 46. It was assumed that the formation of the dithiole ring should proceed similarly to the formation of tertiary diisopropylamines. However, in the case of diisopropyl sulfide, only one isopropyl group is activated by the sulfide atom, and then this activation is suppressed during the formation of the dithiolethione ring associated with the sulfur atom (Scheme 22).

\[
\text{S} - \quad + \text{S}_2\text{Cl}_2 + \text{DABCO} \quad \rightarrow \quad \text{S} - \quad + \quad \text{S} - \quad \rightarrow \quad \text{S} - \quad \text{S} - \text{S} -
\]

**Scheme 22.** Reaction of diisopropyl sulfide with disulfur dichloride

Rees and Rakitin continued their study of the reaction of N-ethyl-diisopropylamine with disulfur dichloride by increasing the reaction temperature from -15 °C to 0 °C. Unexpectedly, these conditions led to a completely different reaction, in which the isopropyl groups remain unchanged and the ethyl group was converted to the dichloroacetyl group in 47 (Scheme 9). To extend this reaction to other ethyl or substituted ethyl groups, the reaction of a number of tertiary amines with disulfur dichloride and DABCO was investigated at 0 °C. N-(2-Chloroethyl)diisopropylamine gave the same dichloroacetyl product 47 as Hünig's base. Similar products were obtained from diethylisopropylamine and triethylamine (Scheme 23).

Further investigation of the reaction of triethylamine with a mixture of disulfur dichloride and DABCO gave even more unexpected results. When a 1:1 mixture of disulfur dichloride and DABCO was kept for 1 hour at room temperature (the authors suggest the formation of complex 1 in this case), the addition of triethylamine leads to the formation of two completely new and unexpected substances - thienopentathiepine 48a and heptathiocane 49a (Scheme 24).\(^{40}\) The first compound is the product of an unprecedented conversion of triethylamine to pentathiepine, in which a thiophene ring is created from two N-ethyl groups to form a carbon-carbon bond between the unactivated methyl groups. We found that these two products were not interconverted under the reaction conditions and were presumably formed in simultaneous, competing reactions. The structure of heptathiocane 49a was confirmed by X-ray diffraction analysis.

Scheme 24. Reaction of triethylamine with complex 1.

Because these are ethyl group reactions, Et\(_3\)N is the preferred substrate. As expected, similar reactions were observed with other tertiary N-ethylamines, but with lower product yields. Diethyl-n-propylamine, ethylidiisopropylamine, benzylidiethylamine, dibenzylethylamine, and N-ethylpiperidine form thienopentathiepines 48 (1–28%) and the corresponding heptathiocanes 49 (3–10%) (Scheme 25). The structure of bis-piperidinothienopentathiepine was also confirmed by X-ray diffraction analysis. Although the yields of these products are generally low, they are easy to produce in one pot from cheap feedstock. The conversion of Et\(_3\)N to pentathiepine and heptathiocan is assumed to be the result of a series of cascade
reactions, including the oxidation of one ethyl group and a number of other transformations. The isolated products, thienopentathiopins 48 and heptathiocanes 49, are likely the most stable members of polysulfur rings containing two and one sp² carbon atoms, respectively.

Scheme 25. Synthesis of thienopentathiopins 48 and heptathiocanes 49.

One of the most interesting discoveries was that disulfur dichloride forms reactive complexes with some tertiary amines at low temperature and with 1,4-diazabicyclooctane (DABCO) at room temperature. A mixture of equimolar amounts of S₂Cl₂ and DABCO in chloroform, stored for one hour at room temperature prior to use, gave various reactions with different products from those formed by simultaneous mixing of the heterocycle, S₂Cl₂, and DABCO. Assuming that complexes were formed between S₂Cl₂ and DABCO, their solutions in chloroform were studied by infrared spectroscopy. The S-S absorption band in a 1:1 mixture was shifted from 540 to 580 cm⁻¹, and the S-Cl in S₂Cl₂ absorption bands (υ 436 and 452 cm⁻¹) were present in a 1:1 mixture of S₂Cl₂ and DABCO, but disappeared when a second mole of DABCO was added. Based on these data, it is suggested that a 1:1 mixture predominantly contains complex 1, and a 1:2 mixture predominantly contains complex 2 (Scheme 26).

Scheme 26. Complexes of S₂Cl₂ and DABCO.

5. Synthesis of fused 1,2,3,4,5-pentathiopins

Rees and co-workers discovered an unusual synthesis of pentathiopins fused to another heterocyclic ring. They found that the reaction of simple nucleophilic heterocycles, such as pyrroles and thiophene, as well as their tetrahydro derivatives, with disulfur dichloride and DABCO results in a simple, one-step synthesis of mono- and previously undescribed bis-pentathiopins. This new transformation was discovered unexpectedly while studying the reaction of N-isopropylpyrrole with disulfur dichloride in an attempt to obtain N-1,2-dithiole-3-thione 50 (Scheme 27). However, it turned out that the pyrrole ring is more reactive than the isopropyl group. The simplicity of this unusual reaction and the availability of the reagents have shown the need for systematic study to find the best conditions for the synthesis of pentathiopins and explore its limits.
Scheme 27. Discovery of fused 1,2,3,4,5-pentathiepins synthesis.

Treatment of N-methylpyrrole with disulfur dichloride and DABCO yielded dichloropyrrolopentathiepine 51a in 50% yield. In the formation of 51a from N-methylpyrrole, the pentathiepine ring fused with the pyrrole ring, and both α-positions of pyrrole were chlorinated. Unsurprisingly, 2,5-dichloro- and 2-chloropyrroles gave pyrrolopentathiepine 51a under similar conditions, and in higher yields (Scheme 28).

Scheme 28. Synthesis of N-methyl dichloropyrrolopentathiepin 51a.

As S₂Cl₂ can also oxidize a pyrrolidine ring to a pyrrole ring, we introduced readily available N-alkyl derivatives of pyrrolidine into a similar reaction. N-Methyl-, N-ethyl, N-isopropyl-, and N-tert-butylpyrrolidines formed the corresponding N-alkyl dichloropentathiepinopyrroles 51 as the main products in low to moderate yields (16–31%). Additionally, N-methylpyrrolidine gave a small amount of non-chlorinated compound 52a (5%) with a pentathiepine ring conjugated by a 2,3-pyrrole bond, N-ethylpyrrolidine gave monochlorinated product 53, and N-isopropylpyrrolidine gave the bispentathiepine 54, which is the first and only bispentathiepine known so far (Scheme 29).
Scheme 29. Reaction of \( N \)-alkylpyrrolidines with \( S_2Cl_2 \).

Disulfur dichloride exhibited both sulfurating (formation of a pentathiepin ring) and a chlorinating (chlorination of the pyrrole ring) properties in these transformations. Complex 2, prepared from disulfur dichloride and two equivalents of DABCO, should exhibit predominantly sulfurating, rather than chlorinating, activity. We used it in the reaction with nucleophilic heterocycles. Indeed, the reaction of all \( N \)-alkylpyrrolidines with complex 2 selectively gives \( N \)-alkylpentathiepinopyrroles 52 in moderate yields; chlorinated products were not found in any of these reactions (Scheme 30). The same products were obtained from \( N \)-alkylpyrroles, but a smaller amount of complex 2 must be used to carry out the selective process. The yields of pentathiepines 52 were close to those obtained from pyrrolidines. \( N \)-Isopropylpyrrole selectively gave bis-pentathiepine 54.

Scheme 30. Selective synthesis of pentathiepinopyrroles 52 and 54.

Even milder conditions have been used to prepare thienopentathiepin and pentathiepinofuran 55 from the corresponding heterocycles. The reaction of these heterocycles with a mixture of disulfur dichloride and \( N \)-ethyldiisopropylamine at a low temperature (-10 °C) gives pentathiepines 55, albeit in low yields (Scheme 31).
Scheme 31. Synthesis of thienopentathiepin and pentathiepinofuran 55.

We extended these reactions to other heterocycles, with moderate success. N-Alkylindoles reacted like pyrroles to give pentathiepines 56 in moderate yields, and tetrahydrothiophene gave the corresponding pentathiepine 57 in good yield (Scheme 32). Unfortunately, more aromatic heterocycles such as thiophene, benzothiophene, and furan did not react with complex 2.

Scheme 32. Reaction of N-alkylindoles and tetrahydrothiophene with complex 2.

Little is known about the nature of all these reactions, although possible general reaction routes have been proposed, including dehydrogenation of tetrahydroaromatic compounds, chlorination and sulfuration of aromatic compounds and their conversion to -SSCl derivatives, and the formation of a pentathiepin ring.

If the pyrrole α-positions are substituted, the pentathiepin ring is added at the 3,4-pyrrole bond to form pentathiepinopyrroles 58 in moderate yield. A study of the synthesis of pentathiepinopyrroles from 2,5-dimethylpyrroles showed that the best yields of pentathiepines 58 were obtained using complex 1 as a reagent at a low temperature (0 °C). At room temperature, pentathiepins 58 gave bis(dithiolo)pyrroles 59 in high yields with complex 1 (Scheme 33). Although pentathiepin rings and methyl groups usually do not react with mixtures of S2Cl2 and DABCO at room temperature, pyrroles 58 containing both of these fragments reacted in an extensive cascade sequence. Presumably, the electron-releasing pyrrole nitrogen activated 58 by attacking either the pentathiepin ring or the methyl group with an electrophilic reagent. A plausible mechanism for this transformation has been proposed.
Scheme 33. An unusual route from 2,5-dimethylpyrroles to bis(dithiolo)pyrroles 59.

Pyrrolopentathiepin 60 was isolated as a minor side product in a very curious and completely unexpected reaction between acetophenone oxime and disulfur dichloride in the presence of pyridine and o-aminophenol (Scheme 34). 17

Scheme 34. Synthesis of pyrrolopentathiepin 60.

6. Development of the chemistry of disulfur dichloride after the death of Professor C. W. Rees

After the death of Professor Rees, his ideas were successfully developed by his coworker Professor O. Rakitin.

6.1 Synthesis of 1,2,5-thiadiazoles

Rakitin et al. showed that the reaction of vic-glyoximes with S2Cl2 and pyridine in acetonitrile at room temperature gives selectively monocyclic 1,2,5-thiadiazoles 61 in moderate yields. Treatment of the same reagents at low temperature (5 °C) leads to the formation of rare 1,2,5-thiadiazole-2-oxides 62 (Scheme 35). 47 Not surprisingly, 1,2,5-thiadiazole N-oxides 62 were converted in high yields to thiadiazoles 61 by treatment with S2Cl2 and pyridine in acetonitrile at room temperature. Monosubstituted glyoximes gave 4-substituted 3-chloro-1,2,5-thiadiazoles under the same conditions. 48
Scheme 35. Synthesis of 1,2,5-thiadiazoles from vic-glyoximes.

Interesting and somewhat unexpected results were obtained in the reaction of diaminoglyoximes with disulfur dichloride. Treatment of 1,4-dihydroquinoxaline-2,3-dionedioxime 63 with S₂Cl₂ in the presence of pyridine in acetonitrile led to the formation of [1,2,5]thiadiazolo[3,4-b]quinoxaline 64 in moderate yield (Scheme 36). In this case, two processes occurred simultaneously: the formation of a thiadiazole ring from the dioxime fragment and the dehydration of dihydropiperazine into an aromatic pyrazine ring, presumably under the action of disulfur dichloride. The reaction of readily available diaminoglyoxime 65 with S₂Cl₂ in the presence of pyridine in acetonitrile led to [1,2,5]thiadiazolo[3,4-c][1,2,5]thiadiazole 66 in moderate yield (Scheme 36).

Scheme 36. Synthesis of [1,2,5]thiadiazolo[3,4-b]quinoxaline 64 and [1,2,5]thiadiazolo-[3,4-c][1,2,5]thiadiazole 66.

A new and original approach to fused 1,2,5-thiadiazoles was described (Scheme 21). Treatment of ortho-nitroanilines with S₂Cl₂ in the presence of pyridine selectively gave 2,1,3-benzothiadiazoles 67 in moderate yields (Scheme 37). The reaction of 4-amino-3-nitro-1,2,5-oxadiazole 68 with the same mixture led to the formation of [1,2,5]thiadiazolo[3,4-c][1,2,5]thiadiazole 66. However, ortho-nitroaniline and other ortho-aminonitroheterocycles upon treatment with S₂Cl₂ gave products of sulfurization or substitution of nitro and amino groups by chlorine atom, which means that the reaction is very sensitive to the structure of the starting material.
Scheme 37. Synthesis of fused 1,2,5-thiadiazoles from vicinal nitroamines.

6.2 Synthesis of 1,2-dithioles

5-Chloro-1,2-dithiole-3-thiones 69 were synthesized by treating \( N-(2\text{-phthalimidoethyl})-N\text{-alkylisopropylamines} \) with a mixture of disulfur dichloride and DABCO followed by reaction with triethylamine.\(^{51}\) The stability of thiones 69 was attributed to the dipole-dipole interaction between the electron-rich 1,2-dithiole-3-thione ring and the electron-poor phthalimide groups (Scheme 38).

Scheme 38. Synthesis of \( N-(2\text{-phthalimidoethyl})-N\text{-alkylisopropylamines} \) 69.

Rakitin and collaborators decided to use readily available 5-chloro-1,2-dithioles 44 in reactions with disulfur dichloride. Treatment of these compounds with \( S_2Cl_2 \) and DABCO in acetonitrile, a solvent rarely used in \( S_2Cl_2 \) reactions, led to the formation of ketothione bisdithiolothiazines 70 after treatment with triethylamine as the base.\(^{52}\) Bisdithioloketothiones 70 were obtained selectively with moderate to high yields (Scheme 39). To the best of our knowledge, this is the first time that a chlorine substituent in salt 71 has been replaced by sulfur under the electrophilic action of disulfur dichloride and a base.
**Scheme 39.** Synthesis of bisdithiolothiazine ketothiones 14.

To expand the sulfurizing ability of S₂Cl₂ in reactions with 5-chloro-1,2-dithioles, the reaction of N,N-bis(5-chloro-3-oxo[1,2]dithiol-4-yl)amines 41 with disulfur dichloride and base was studied. Treatment with S₂Cl₂ and triethylamine gave bis-dithiolothiazines 72 in high yields. The novelty of these transformations is the replacement of chlorines by sulfur in the reaction with electrophilic disulfur dichloride and its mixtures with tertiary amines.

![Scheme 39](image)

**Scheme 40.** Reaction of bis(dithiolyl)amines 41 with S₂Cl₂.

Professor Rees showed that N-isopropyl groups with S₂Cl₂ can be converted into N-(1,2-dithiole-3-thiones) (see Section 4). Nitrogen heterocycles containing methyl and CH groups in the ortho positions, such as 2-methylindoles, which are readily and commercially available, are structurally similar to the isopropyl group and can be considered as potential intermediates in the synthesis of dithioloindolothiones. The reaction of 1,2-dimethylindole 73a with a five-fold excess of complex 1 in chloroform for 48 h at room temperature, after treatment with Et₃N, formed dithiolothione 74a in moderate yield (34%). It is not surprising that complex 2, which is more selective sulfurating agent, reacts more simply with 73a (R = Me) to form thione 74a (R = Me) in high yield (94%) under the same conditions (Scheme 41). Subsequently, this reaction was extended to other N-substituted 2-methylindoles 73. Fused dithioloindoles 74 were obtained in moderate and high yields from N-alkyl- and N-benzyl-2-methylindoles 73.

![Scheme 41](image)

**Scheme 41.** Synthesis of N-substituted [1,2]dithiolo[4,3-b]indole-3(4H)-thiones 74.

### 6.3 Synthesis of 1,2,3-dithiazoles

Thiéry and Rakitin developed earlier ideas put forward by Professor Rees on the preparation of 1,2,3-dithiazoles from substituted ethanone oximes. They found that 5-one- 75, 5-thione- 76 and 5-phenylimino-1,2,3-dithiazoles 77 can be selectively prepared by reacting various ethanone oximes with disulfur dichloride in the presence of pyridine as the base in acetonitrile, followed by treatment with the appropriate nucleophiles (formic acid, thioacetamide, and aniline) in high to moderate yields (Scheme 42). The key
intermediates in the formation of 1,2,3-dithiazoles were 1,2,3-dithiazolium chlorides 78, which were unstable and converted into keto-, thio-, and arylimino derivatives upon reaction with the corresponding nucleophiles in situ. The yield of dithiazoles 75–77 depends on the reaction conditions, including the reaction time and temperature, the nature of the solvent, and the base used.

Scheme 42. Synthesis of 1,2,3-dithiazoles from ethanone oximes.

Recently, a series of 5-substituted-4-chloro-1,2,3-dithiazolium chlorides 79 were prepared by Koutentis in the reaction of monosubstituted acetonitriles with disulfur dichloride (Scheme 43).55,56 The chloride salts were transformed into the corresponding perchlorates sufficiently stable to be characterized if the 5-substituent was not a readily leaving group.

Scheme 43. Synthesis of monocyclic 1,2,3-dithiazoles from substituted acetonitriles.

6.4 Chalcogen exchange in 1,2,5-oxa- and 1,2,5-selenadiazoles
This reaction, like many other reactions of disulfur dichloride, was discovered by accident. A study of the reaction of 3,4-diamino-1,2,5-oxadiazole with disulfur dichloride and pyridine in acetonitrile showed that, as a result of the reaction, [1,2,5]thiadiazolo[3,4-c][1,2,5]thiadiazole 66 was formed in high yield (Scheme 44) instead of [1,2,5]oxadiazolo[3,4-c][1,2,5]thiadiazole 80.57 The most interesting feature of this transformation is the replacement of the oxygen atom in 1,2,5-oxadiazole ring with a sulfur atom in reaction with disulfur...
dichloride. Later it was shown that another oxadiazole derivative, 4-amino-3-nitro-1,2,5-oxadiazole 68, can also undergo a similar transformation with \( \text{S}_2\text{Cl}_2 \).\(^{49}\)

![Scheme 44. Synthesis of \([1,2,5]\)thiadiazolo[3,4-c][1,2,5]thiadiazole 66 from 3,4-diamino-79 and 3-nitro-4-amino-1,2,5-oxadiazoles 68.](image)

Similar processes were found for the reactions of piperazinoxadiazoles: in all cases, tricyclic bis([1,2,5]thiadiazolo)[3,4-b;3’,4’-e]pyrazine 81 was isolated in moderate to high yields (Scheme 45).\(^{47,58}\) Surprisingly, other unfused 1,2,5-oxadiazoles, 2,1,3-benzooxadiazoles, and 5,6-disubstituted [1,2,5]oxadiazolo[3,4-b]pyrazines in these conditions did not react with \( \text{S}_2\text{Cl}_2 \). An analysis of these results led the authors to the conclusion that the successful conversion of 1,2,5-oxadiazoles to 1,2,5-thiadiazoles requires the presence of one or two \( \text{NH}_2 \) or \( \text{NH} \) groups attached directly to the oxadiazole ring in the molecule.

![Scheme 45. Synthesis of bis([1,2,5]thiadiazolo)[3,4-b;3’,4’-e]pyrazine 81.](image)

The reaction of replacing a chalcogen atom with a sulfur atom under the action of disulfur dichloride turned out to be applicable for 1,2,5-selenadiazoles as well. The reaction of 1,2,5-selenadiazoles 82 fused with electron-withdrawing heterocycles such as 1,2,5-thiadiazole, 1,2,5-selenadiazole, quinoxaline, etc., with \( \text{S}_2\text{Cl}_2 \) in DMF led to the corresponding mono- and bis(1,2,5-thiadiazoles) 83 in moderate to good yields (Scheme 46).\(^{58}\) Using an excess of disulfur dichloride for heterocycles containing two selenadiazole rings, both selenium atoms were replaced by sulfur atoms to form bis(1,2,5-thiadiazoles). 2,1,3-Benzoselenadiazole and 3,4-diphenyl-1,2,5-selenadiazole do not react with disulfur dichloride in organic solvents even under extreme conditions (boiling in acetonitrile or heating in DMF at 100 °C for 10 h) and were isolated from reaction
mixtures in almost quantitative yields. Apparently, the key condition for the successful replacement of a selenium atom in a heterocycle with a sulfur atom is the presence of a strong electron-withdrawing heterocycle attached to selenadiazole.

Scheme 46. Synthesis of mono- and bis(1,2,5-thiadiazoles) 83 from the corresponding 1,2,5-selenadiazoles 82.

6.5 Synthesis of sulfur diimides

Direct and efficient synthesis of symmetrical sulfur diimides from commercial anilines and disulfur dichloride was developed by Rakitin et al. It was shown that treatment of anilines with a mixture of S₂Cl₂ and DABCO in chloroform followed by reflux led to the formation of symmetrical sulfur diimides 84 in high yields (Scheme 47).<sup>59</sup> 4H-1,2,4-Triazol-4-amine 85 unexpectedly gave tetrathiusulfur tetranitride under these conditions in moderate yield.

Scheme 47. Synthesis of diarylsulfur diimides 84 from anilines.

7. Conclusions

The reactions described show that the methodology developed by Professor Rees represents a rapid and convenient route to sulfur-containing heterocyclic systems, which in many cases are difficult or impossible to obtain using traditional methods. As a result, these unique heterocycles have a number of features in contrast to carbon-containing compounds, and have promising properties in both the pharmaceuticals and
agrochemical fields,\textsuperscript{13,60,61} as well as compounds with interesting physical properties in optoelectronics,\textsuperscript{62-64} magnetism, and electrical conductivity.\textsuperscript{65,66} All the described reactions show that disulfur dichloride is an important reagent for the synthesis of heterocycles with different numbers of sulfur atoms, or even without sulfur atoms. An important feature of this reagent is that it can add to a molecule not only two sulfur atoms, as one might expect, but also one, three, four, five and even more atoms, and the structure of the final compound often depends on its stability. The wide range of new polysulfur-nitrogen heterocycles, their interesting characteristics, and rapid synthesis methods from readily available materials make this strategy very promising. Professor Rees's role in the development of disulfur dichloride chemistry cannot be overestimated.

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Lidia Konstantinova graduated at M. V. Lomonosov Moscow Institute of Fine Chemical Technology in 1972. She received her PhD in 1994 and her Doctor of Science Degree in 2009 in the N.D. Zelinsky Institute of Organic Chemistry, where she is working since 2009 as a Main Researcher. She collaborated with Professor C.W. Rees from 1997 up to his death in 2006 at Imperial College (London, UK). She has published with Professor C.W. Rees 18 scientific papers and reviews. Her scientific interests include the synthesis of polysulfur-nitrogen heterocyclic systems.

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Sivaprasad Sivadasan was born in India (1967) and emigrated to London, UK at the age of 10. He graduated in chemistry (BSc.) from North London university in 1989 and worked at GlaxoSmithKline, (1989-1990). He left GSK to do is PhD. at Imperial College London and obtained his doctorate (1990-1993) under the supervision of Professor Charles W. Rees. After his graduation he worked at Merck Generics (1994-1998) as a development chemist. In 1998 he moved to Sweden to work for AstraZeneca (AZ) as Senior Scientist. He left AZ in 2013 as Global Stability Manager. Since then, he has obtained a teachers degree from Stockholm university (2016-2018). Siva is a high school teacher, teaching chemistry and mathematics, currently working in a juvenile detention center.
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Tomás Torroba was born in Valladolid, Spain, 1956, PhD from the University of Valladolid, 1982, under the supervision of Prof. Angel Alberola, current position as Professor of Organic Chemistry, Department of Chemistry, University of Burgos since 1998. Assistant in the Department of Organic Chemistry of the Faculty of Science, University of Valladolid, 1978-1982, Lecturer in the Department of Organic Chemistry, Faculty of Veterinary Medicine, University of Extremadura, 1983-1998, Dean of the Faculty of Science, University of Burgos, 2000-2004. Main research topics: Sulfur-Nitrogen Heterocyclic Compounds, under the supervision of Professor Charles W. Rees, 21 articles from 1993 to 2001, Multicomponent Reactions with Dr. S. Marcaccini, Univ. Florence, Italy, 38 articles from 1987 to 2013, nowadays working in Chemical Sensors and Supramolecular Chemistry, a total of 140 articles throughout his academic career (WoS), h-index: 32.

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