process was continued for two hours sweeping with a stream of nitrogen. Here 0.45 g. of II resulted, m.p. 137°. The solid samples were combined and recrystallized from a mixture of ethyl acetate and ethanol, m.p. 147.5–148°, mixed m.p. with an authentic sample of II (m.p. 148.5°) 148–148.5°. In another blank run on a second batch of Raney nickel, bubbling the air stream through (rather than blowing over) the catalyst bed, 1.35 g. of II, m.p. 145° resulted after four hours. No. II was formed on adding a solution of I to the supernatant ethanol over Raney nickel at room temperature even when the catalyst had been standing for over a year.

Raney Nickel, β-Thionaphthol and Ethanol.—β-Thionaphthol (3.2 g.), Raney nickel (30 g.) and ethanol (60 ml.) were refluxed in an air stream as above. A precipitate of II began forming in the I solution after forty minutes. At the outset of precipitation of II a sample of the reaction mixture was withdrawn, filtered of catalyst and evaporated dry. The residue smelled of naphthalene and gave a negligible qualitative test for sulfur, suggesting completion of the reaction. After 3.5 hours 0.50 g. of II was collected. The catalyst was filtered, rinsed with hot ethanol and the filtrate evaporated to dryness, leaving 2.0 g. (78%) of naphthalene, m.p. after recrystallization from dilute ethanol 78–80°, no mixed m.p. depression with an authentic sample. The theoretical quantity of II in the above reaction would be 4.5 g. if the hydrogen of Equation (2) were involved in the reductive desulfurization.

When 2.5 g. of naphthalene was dissolved in a comparable quantity of ethanol and distilled to dryness 2.0 g. (80%) remained. This suggests that the actual production of naphthalene in the above experiment was quantitative.

One ml. of acetaldehyde, spent Raney nickel (30 g.) and ethanol (60 ml.) were refluxed in the usual apparatus, sweeping with an air stream. The formation of II in the bubbler was instantaneous. After 90 minutes 3.95 g. (99%) of II was collected, m.p. and mixed m.p. 145–146°. This result indicates that any acetaldehyde produced by Reaction (2) would be quantitatively accounted for.

Raney Nickel, β-Thionaphthol and Benzene.—Raney nickel (30 g.) under absolute ethanol was filtered, rinsed with benzene and transferred to a flask under 70 ml. of benzene. The mixture was distilled (*ca.* 20 ml.) to remove remaining ethanol azeotropically, then treated with β-thionaphthol (3.2 g.). After four hours of reflux the catalyst was filtered and rinsed with hot benzene. It was still strongly pyrophoric, indicating the presence of adsorbed hydrogen. The filtrate was evaporated leaving 2.0 g. (78%) of naphthalene, m.p. 78–80° after recrystallization from dilute ethanol.

"Hydrogen-free" Raney Nickel.—This was made by heating Raney nickel at 200° at oil-pump pressure, after the general method of Hauptmann and Wladislaw.[3] Benzene was admitted over the nickel after completion of the heating without first breaking the vacuum.

"Hydrogen-free" Raney Nickel, β-Thionaphthol and Ethanol.—About 12 g. of "hydrogen-free" Raney nickel was decanted of benzene and washed into the usual apparatus with 80 ml. of ethanol. Approximately 15 ml. of solvent was distilled to remove residual benzene. β-Thionaphthol (1.5 g.) was added, and the mixture refluxed in an air stream for 3.5 hours. Before the first hour the white reaction product was noticeable in the flask containing the catalyst. During this period 0.18 g. of II was formed in the bubbling tower. The catalyst was filtered, rinsed thoroughly with boiling acetone and the filtrate stripped of solvent to give 0.75 g. (50%) of β-naphthyl disulfide, m.p. after recrystallization from a mixture of acetone and ethanol 141.5–142°. A mixed m.p. with an authentic sample prepared below was undepressed. Similar results were obtained with "hydrogen-free" Raney nickel when benzene replaced ethanol as the solvent.

β-Naphthyl Disulfide.—β-Thionaphthol (3.2 g.) was dissolved in acetic acid (50 ml.) and treated with 30% hydrogen peroxide (1.2 g., 6% excess) at 25°. On standing overnight the flask filled with tan crystals, 2.15 g. (68%), m.p. 139–140°. After two recrystallizations from a mixture of acetone and ethanol the m.p. was constant at 141–141.5°. Cleve[7] gives the m.p. of β-naphthyl disulfide as 139°.

Raney Nickel, Ethyl Sulfide and Ethanol.—Ethyl sulfide (1.3 g.), Raney nickel (20 g.) and ethanol (40 ml.) were refluxed in the usual apparatus. After 90 minutes II began to precipitate in the bubbler and 0.97 g. was filtered after three hours. Hydrogen sulfide was noted on adding hydrochloric acid to the spent catalyst. The theoretical quantity of acetaldehyde from Reaction (2) would here give 3.4 g. of II. About one gram would be predicted from the previous runs. The amount produced is thus only equivalent to the blank.

(7) P. T. Cleve, *Ber.*, **21**, 1099 (1888).

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Stereochemical Paths of Reductive Desulfuration

BY WILLIAM A. BONNER

To determine the stereochemical fate of an asymmetric center adjacent to a sulfur atom during reductive desulfuration with Raney nickel, 2-phenyl-2-phenylmercaptopropionic acid has been synthesized and resolved into both enantiomorphs. The resolved acids were converted into their amides, and the latter subjected to reductive desulfuration. The products obtained were completely racemic, a result which accords with a previously proposed free radical mechanism. When the enantiomorphic 2-phenyl-2-phenylmercaptopropionamides were oxidized to the corresponding sulfones, however, and the sulfones desulfurated with Raney nickel, the products were optically active, enantiomorphic, and about 90% optically homogeneous. Hydrogen bonding between the sulfone and amide groups has been eliminated as a possible explanation for the differing stereochemical paths followed by sulfides and sulfones on desulfuration. The results indicate that sulfones are not desulfurated *via* intermediate sulfides, and that mechanistically the two desulfuration paths are distinct. An alternative mechanism involving direct displacement and inversion is postulated for sulfone desulfuration, and optical evidence is presented suggesting that inversion indeed occurs.

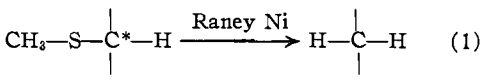
Despite a rapidly growing literature concerning practical applications of the Raney nickel catalyzed reductive desulfuration process, very little is known regarding the essential nature of this useful reaction. While, as considered later, several mechanistic proposals have been advanced little actual experimental work has been undertaken to provide mechanistic information. In particular, the stereochemical course of reductive desulfuration has not been elucidated. While it is known from work with carbohydrates,[1] biotin[2] and amino acids[3] that the conditions of reductive desulfuration do not engender change in an asymmetric center situated at a

(1) H. G. Fletcher, Jr., and N. K. Richtmyer, "Advances in Carbohydrate Chemistry," Vol. V, Academic Press, Inc., New York, N. Y., 1950, chap. I; W. A. Bonner and J. E. Kahn, THIS JOURNAL, **73**, 2241 (1951); W. A. Bonner, *ibid.*, **73**, 2659 (1951).

(2) V. du Vigneaud, D. B. Melville, K. Folkers, D. E. Wolf, R. Mozingo, J. C. Keresztesy and S. A. Harris, *J. Biol. Chem.*, **146**, 475 (1942).

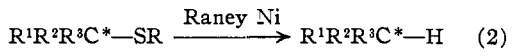
(3) R. Mozingo, D. E. Wolf, S. A. Harris and K. Folkers, THIS JOURNAL, **65**, 1013 (1943).

distance from the sulfur atom, the fate of an asymmetric center adjacent to the sulfur atom is unknown. The only instances where the latter type of compounds have been desulfurated appear in the investigations of Reichstein and co-workers[4] who studied desulfurations such as (1) in the carbohydrate series. Here critical stereochemical informa-



(1)

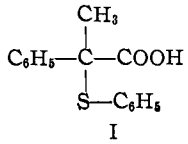
tion unfortunately cannot be deduced because the asymmetric sulfur-bearing carbon becomes symmetric in the final product. To gain critical stereochemical information about reductive desulfuration we have undertaken a study wherein the carbon atom adjacent to the sulfur is asymmetric not only in the starting material, but also in the final product, as typified in (2). Our observations indicate that the oxidation state of the sulfur atom in the



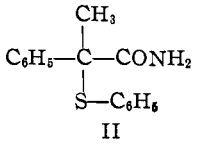
(2)

starting material determines the stereochemical path followed during desulfuration.

2-Phenyl-2-phenylmercaptopropionic acid (I), the key substance in the present study, was synthe-



I



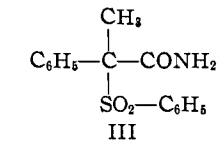
II

sized by the following reaction sequence. Ethyl atrolactate with phosphorus pentachloride produced ethyl 2-chloro-2-phenylpropionate. Reaction of the latter with sodium phenyl sulfide in a mixture of chloroform and ethanol produced ethyl 2-phenyl-2-phenylmercaptopropionate. Alkaline hydrolysis of this ester produced the desired I in good yield. In addition, however, the alkaline hydrolysis was accompanied by some carbon–sulfur cleavage, since small amounts of thiophenol were noted as a by-product. The structure of I was established by Raney nickel desulfuration, whereby 2-phenylpropionic acid was isolated in 41% yield and identified through its crystalline amide. If I was converted to its amide (II) prior to desulfuration, 2-phenylpropionamide was isolable directly in 85% yield after treatment with Raney nickel. The low yield in the former instance was probably due to reaction of I or its product with the nickel catalyst during the prolonged refluxing, producing insoluble nickel salts. As a consequence, subsequent desulfurizations were studied on derivatives of I rather than on I itself.

By repeated recrystallization of its (+)-1-phenylethylammonium salt, I was resolved into (+)-2-phenyl-2-phenylmercaptopropionic acid. Treatment of the acid recovered from the mother liquors of the above resolution with (−)-1-phenylethylamine led to the isolation of the antipode, (−)-2-phenyl-2-phenylmercaptopropionic acid. Both antipodes were converted to their amides (± II) prior to desulfuration experiments.

When either of these amides (± II) was refluxed with Raney nickel in ethanol for about five hours, racemic 2-phenylpropionamide resulted, indicating that desulfuration of a sulfide is accompanied by complete racemization. That this was a consequence of mechanism only was shown by the fact that when (−)-2-phenylpropionamide was treated with Raney nickel under identical conditions, it was recovered unchanged. The above racemization thus occurred *during* the desulfuration process, not after the product was formed.

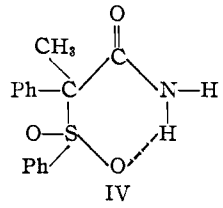
The enantiomorphic amides (± II) were next oxidized to the corresponding sulfones, (± III). When either of these was desulfurated under the usual conditions, the 2-phenylpropionamides ob-



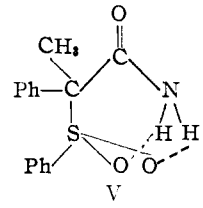
III

tained were optically active and enantiomorphic and, indeed, their rotations indicated that racemization during desulfuration had occurred to the extent of only about 10%.

An explanation of the strikingly divergent stereochemical results noted with sulfides and sulfones was first sought in terms of possible structural differences in the molecules. Cyclic hydrogen bonded structures such as IV or V might be extremely probable for the sulfone but must be impossible for the sulfide. In ethyl (−)-2-phenyl-2-benzenesulfonyl-

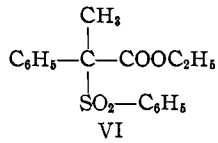


IV



V

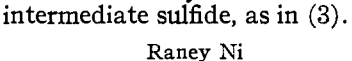
propionate (VI) such hydrogen bonding involving



VI

the sulfone group is impossible and could not enter as a structural feature dictating the stereochemical path. Desulfuration of VI, however, again led to an optically active ethyl 2-phenylpropionate whose rotation once more suggested only about 10% racemization. It was apparent, therefore, that differences in the stereochemical courses of the two reactions must be due to differences in mechanism, rather than to differences in structure alone.

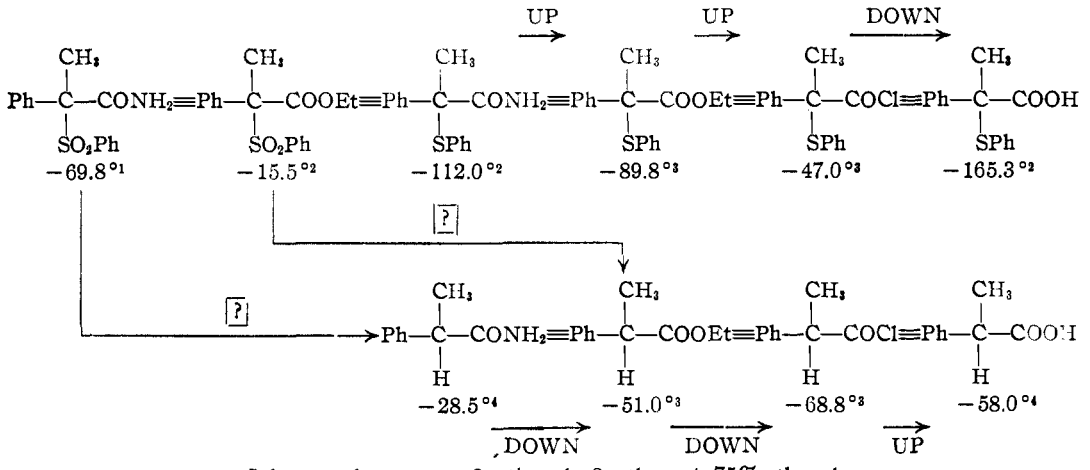
Before discussing mechanisms in accord with the above stereochemical facts, it should be emphasized that sulfones clearly cannot suffer desulfuration *via* an intermediate sulfide, as in (3). If such were the



(3)

course of sulfone hydrogenolysis, the product must again be racemic. It is therefore obvious that the

(4) R. Jeanloz, D. A. Prins and T. Reichstein, *Experientia*, **1**, 336 (1945); *Helv. Chim. Acta*, **29**, 371 (1946); A. C. Maehly and T. Reichstein, *ibid.*, **30**, 496 (1947); M. Gut, D. A. Prins and T. Reichstein, *ibid.*, **30**, 743 (1947).



Solvents: 1, acetone; 2, ethanol; 3, ether; 4, 75% ethanol.

Fig. 1.—Comparison of optical rotatory trends for derivatives of 2-phenyl-2-phenylmercaptopropionic acid and 2-phenylpropionic acid. (Optical rotations not recorded in the present study are taken from the work of Levene, Mikeska and Passoth.)[16]

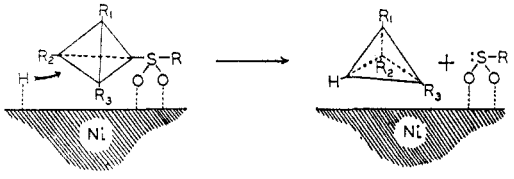
sulfur–carbon bond of the sulfone undergoes cleavage prior to any rupture of the sulfur–oxygen linkage.

The most detailed mechanistic postulates regarding the reductive desulfuration of compounds at the sulfide level are those recently advanced by Hauptmann and Wladislaw.[5] Arguing from their isolation of diaryls, aryl sulfides and stilbenes following the action of "hydrogen-free" or "hydrogen-poor" nickel on aromatic mercaptals, thioesters, and related compounds, these investigators propose a free radical mechanism for desulfuration. Since ordinary esters were found stable under desulfuration conditions, chemisorption, presumably involving the unshared sulfur electrons, was postulated as the initial step. This weakening the carbon–sulfur bond permits detachment of a free radical. In the presence of adsorbed hydrogen such a radical is reduced to the hydrocarbon stage. In an absence or deficiency of adsorbed hydrogen, such radicals may combine with one another to form diaryls or other higher molecular weight products. This hypothesis is roughly schematized in (4).

$$\begin{aligned} &\text{R–S–R} + \text{Ni}\cdot \longrightarrow \text{R}\cdot + \text{Ni–S–R} \\ &\text{R}\cdot + \text{H}\cdot(\text{adsorbed}) \longrightarrow \text{RH, or} \\ &2\text{R}\cdot \longrightarrow \text{R–R} \end{aligned} \qquad (4)$$

Our present observations of racemization attending sulfide desulfuration, and our recent demonstration[6] that surface adsorbed hydrogen is the source available for reductive desulfuration, are in accord with these postulates. The known optical instability of free radicals[7] strongly confirms the notion that sulfide desulfuration, accompanied by racemization, is a free radical process.

On the other hand it is clear that sulfone desulfuration, accompanied by almost complete retention of optical activity, is probably not a free radical process, at least in the sense of equation (4). Similarly, if Hauptmann's suggestion[5] of chemisorption at the sulfur atom of sulfides is correct, such could not operate in the case of sulfones, since in sulfones there are no unshared electrons in the sulfur orbitals. We propose the following alternative mechanism as applying to sulfone desulfuration. Adsorption on the catalyst surface occurs through the oxygen atoms of the sulfone. The adsorbed molecule is then attacked by, or attacks, an adjacent adsorbed hydrogen atom in such a way that the carbon–sulfur bond is broken, and an optically active reduction product is simultaneously formed. One suggestion for this process is illustrated in (5).



(5)

A replacement such as (5) must in all probability be attended by inversion. An examination of the optical rotatory data in the series of compounds involved strongly suggests that inversion has indeed occurred during the desulfurations of III and VI. In Fig. 1 are given optical rotations of the various derivatives involved. Compounds of known configurational similarity are so indicated by equivalence signs. The points of questionable inversion are indicated with question marks. Freudenberg and co-workers[8] have employed a principle of "uniform rotational trends" to establish configurational similarity. If the rotational trends are identical in a series of derivatives of two optically active substances of reasonable structural similarity, then these substances are believed to have identical configurations. In Fig. 1, however, it is notable that there is a precise inversion in rotational trends for the two series, even though they are rather limited. While not conclusive, this strongly suggests that the two series have opposite configurations and accords

(5) H. Hauptmann and B. Wladislaw, THIS JOURNAL, **72**, 707, 711 (1950).

(6) W. A. Bonner, *ibid.*, **72**, 1034 (1950).

(7) R. L. Shriner, R. Adams and C. S. Marvel in Gilman "Organic Chemistry," 2nd. Edition, Vol. I, John Wiley and Sons, Inc., New York, N. Y., 1943, pp. 383–388; G. W. Wheland, "Advanced Organic Chemistry," 2nd Edition, John Wiley and Sons, Inc., New York, N. Y., 1949, pp. 713–716.

(8) K. Freudenberg, "Stereochemie," F. Deuticke, Leipzig and Vienna, 1933, p. 695 ff.

with our postulate that inversion attends the reductive desulfuration of sulfones.

Experimental

Ethyl 2-Chloro-2-phenylpropionate.—Ethyl atrolactate b.p. 99–100° (8 mm.) was synthesized in 86% crude yield by esterification of atrolactic acid, prepared in turn by hydrolysis of acetophenone cyanohydrin.[9] This ester (48 g.) was treated with phosphorus pentachloride (56 g.) over a period of 20 minutes under ice-cooling. The homogeneous mixture stood at room temperature overnight, then was diluted with 35–55° ligroin (200 ml.). The solution was washed four times with ice-water, then with ice-cold bicarbonate solution. It was dried over anhydrous sodium sulfate and the solvent distilled to give 49.1 g. (94%) of clear oil, 47.4 g. of which distilled at 104–108° (21 mm.). The above is a modification of the procedure of McKenzie and Clough.[10]

Ethyl 2-Phenyl-2-phenylmercaptopropionate.—Thiophenol (25.2 ml., 10% excess) was dissolved in alcohol (100 ml.), then neutralized with a solution of sodium (5.9 g.) in ethanol (200 ml.). The neutral solution was added to a solution of ethyl 2-chloro-2-phenylpropionate (47.4 g.) in chloroform (100 ml.), and the mixture boiled under reflux for 90 minutes. The precipitated sodium chloride (10.7 g. (82%)) was filtered and rinsed with chloroform, and the filtrate vacuum concentrated at 100° to *ca.* 150 ml., then cooled and poured into water. The mixture was extracted twice with 35–55° ligroin (125-ml. portions), and the extract washed twice with water, twice with 10% sodium hydroxide solution, and twice with water. The extract was then dried over anhydrous sodium sulfate, and the solvent distilled to produce 57.0 g. (89%) of amber oil, of which 53.4 g. distilled at 175–185° (7 mm.). In a larger synthesis the b. p. was 179–194° (10 mm.), mostly 183° (10 mm.), and a middle cut was taken for characterization: d^{20}_{20} 1.127; $n^{26}D$ 1.5785; $M^{20}D$, calcd. for $C_{17}H_{18}O_2S$, 83.2; found, 83.9.

Anal. Calcd. for $C_{17}H_{18}O_2S$: C, 71.30; H, 6.34; S, 11.18. Found[11]: C, 71.45, 71.61; H, 6.33, 6.46; S, 11.43, 11.66.

2-Phenyl-2-phenylmercaptopropionic Acid.—Ethyl 2-phenyl-2-phenylmercaptopropionate (50 g.) was stirred vigorously on the steam-bath with 10% sodium hydroxide solution (250 ml.) for seven hours, after which the mixture was homogeneous. The cooled solution was extracted with ligroin, and the extract discarded. The alkaline portion was cautiously acidified with hydrochloric acid (75 ml.), then steam distilled until the distillate was clear and odorless. The residue was cooled, extracted with a mixture of ether and ligroin, and the extract washed with water, dried over anhydrous sodium sulfate, decolorized by filtration through a Norit bed, and stripped of solvent to leave 36.5 g. (81%) of clear sirup. This was dissolved in hot benzene (10 ml.) and treated with boiling 35–55° ligroin (100 ml.). On cooling 26.2 g. of solid, m. p. 86–89°, resulted. This was recrystallized by dissolving in hot benzene (22 ml.) and adding boiling ligroin (120 ml.). Several such recrystallizations gave the pure material, m.p. 104.5–105°.

Anal. Calcd. for $C_{15}H_{14}O_2S$: C, 69.79; H, 5.46; S, 12.43; neut. equiv., 258.3. Found: C, 69.31, 69.33; H, 5.30, 5.36; S, 12.22, 12.16; neut. equiv., 257.0.

The steam distillate above was saturated with salt to produce 4.8 g. of thiophenol, identified by odor, solubility in alkali, and conversion[12] to phenyl 2,4-dinitrophenyl sulfide, m. p. 121°.

2-Phenylpropionamide.—Sodium (4.8 g., 5% excess) was converted to "sand" in boiling toluene. The cooled solvent was decanted, and the sodium transferred with anhydrous ether (300 ml.) to a one-liter, three-necked flask equipped with a mercury-sealed Hershberg stirrer, reflux condenser ($CaCl_2$ tube), and dropping funnel. Phenylacetonitrile (23.4 g.) was added dropwise with vigorous stirring in the presence of glass beads (20 g.). Refluxing was spontaneous, and stirring and refluxing were prolonged for 2.5 hours. At this point methyl iodide (19 ml., 50% excess) was added dropwise, and the turbid mixture stirred under reflux for 90 minutes, cooled, filtered and the cake rinsed thoroughly by suspension in ether and refiltration. The filtrate was concentrated to dryness, leaving 17.3 g. of dark oil, to which 10% sodium hydroxide solution (100 ml.) was added. The mixture was stirred vigorously on the steam-bath for two days, after which it was cooled and extracted twice with ether, discarding the extract. The alkaline portion was acidified with hydrochloric acid, and the resulting oil extracted into ether. The extract was washed with water, dried and evaporated to produce 13.4 g. (37%) of oily 2-phenylpropionic acid. This was heated under reflux for 90 minutes with thionyl chloride (75 ml.), the excess of which was then removed *in vacuo* at 100°. The residue was added dropwise to an excess of chilled ammonium hydroxide, and the resulting solid extracted into ether. The extract was washed with water, dried and decolorized by filtration through Norit, then boiled dry. The residue was recrystallized from benzene and ligroin to produce 5.8 g. of 2-phenylpropionamide, m.p. 97–97.5°. Three further recrystallizations gave a sample of m.p. 97.5°.

Anal. Calcd. for $C_9H_{11}ON$: C, 72.50; H, 7.44; N, 9.38. Found: C, 72.41, 72.44; H, 7.34, 7.42; N, 9.22, 9.36.

The recorded[13] m. p. for this compound is 91–92°. Samples prepared below by reductive desulfuration generally melted closer to 91°, analyzed correctly, and showed no m.p. depression on mixing with the present sample. It is possible that polymorphism explains the present high m.p.

Reductive Desulfuration of 2-Phenyl-2-phenylmercaptopropionic Acid.—The acid (3.5 g.) was heated under reflux with Raney nickel[14] (40 g.) in ethanol (60 ml.) for 15 hours. The mixture was filtered and the nickel rinsed with boiling ethanol. Evaporation of the filtrate left 1.2 g. of a paste which was leached with acetone and ether, then filtered. The filtrate was boiled dry leaving 0.83 g. (41%) of 2-phenylpropionic acid. This was heated under reflux with thionyl chloride (10 ml.) for 90 minutes, the excess thionyl chloride distilled, and the residue added to cold ammonium hydroxide. Extraction of the mixture with benzene, followed by the usual processing, led to 0.15 g. of crude 2-phenylpropionamide. Three recrystallizations from a benzene–ligroin mixture gave shining platelets, m.p. 91.5–92°, mixed m. p. with the above 2-phenylpropionamide 91.5–92°.

2-Phenyl-2-phenylmercaptopropionamide.—2-Phenyl-2-phenylmercaptopropionic acid (2.0 g.) was heated under reflux with thionyl chloride (20 ml.) for 90 minutes, after which the excess of the latter was removed *in vacuo*. The residue was added to cold ammonium hydroxide, and the product extracted into benzene and isolated as before. There resulted 2.1 g. (105%) of amber oil which spontaneously crystallized. Three recrystallizations from a 1:5 mixture of benzene and ligroin gave the pure product, m.p. 88.5–89°.

Anal. Calcd. for $C_{15}H_{15}ONS$: C, 70.00; H, 5.87; N, 5.44; S, 12.44. Found: C, 70.19, 70.21; H, 5.79, 5.97; N, 5.55; S, 12.68.

Reductive Desulfuration of 2-Phenyl-2-phenylmercaptopropionamide.—The amide (1.6 g.) was heated under reflux with Raney nickel (15 g.) in ethanol (50 ml.) for 14 hours. Evaporation of the filtrate gave 0.8 g. (85%) of crude 2-phenylpropionamide. Recrystallization from 15 ml. of a 1:3 benzene–ligroin mixture gave 0.7 g. of solid, m.p. 94.5°, mixed m.p. with the synthetic sample above, 96–97°.

Resolution of 2-Phenyl-2-phenylmercaptopropionic Acid.—The acid (25.8 g.) in ethanol (35 ml.) was treated with a solution of (+)-1-phenylethylamine[15] (12.1 g.) in ethanol (35 ml.). The mixture was boiled, treated with hot water

(9) E. L. Eliel and J. P. Freeman, procedure submitted for publication in "Organic Syntheses."

(10) A. McKenzie and G. W. Clough, *J. Chem. Soc.*, **97**, 2569 (1910).

(11) All microanalyses were performed by the Microchemical Specialties Company, Berkeley, California.

(12) R. W. Bost, J. O. Turner and R. D. Norton, THIS JOURNAL, **54**, 1985 (1932).

(13) H. Janssen, *Ann.*, **250**, 136 (1889).

(14) R. Mozingo, *Org. Syntheses*, **21**, 15 (1941).

(15) A. W. Ingersoll, "Organic Syntheses," Coll. Vol. II, John Wiley and Sons, Inc., New York, N. Y., 1943, p. 506.

(70 ml.), and the salt allowed to crystallize at 0°, filtered, dried and weighed (33.5 g.). The salt was then repeatedly recrystallized by dissolving in hot alcohol and adding one-third its volume of hot water. The quantity of this solvent used in each recrystallization was 4.2 ml. per gram of salt. Crystallization was allowed to proceed at room temperature. The specific rotation of the dried salt was determined after each recrystallization. After eight recrystallizations 4.7 g. of (+)-1-phenylethylammonium (+)-2-phenyl-2-phenylmercaptopropionate resulted as long needles, m.p. 154–155°, $[\alpha]^{25}D$ 196.2° (*c* 0.621, ethanol).

Anal. Calcd. for $C_{23}H_{25}O_2NS$: C, 72.90; H, 6.66. Found: C, 72.38, 72.42; H, 6.53, 6.60.

These were treated with dilute (1:3) hydrochloric acid, and the mixture shaken with ether until the solid was dissolved. The ether extract was washed with water, dried and evaporated to produce 3.15 g. of the dextro acid which crystallized spontaneously. It was recrystallized from benzene (1.5 ml.) to which hot ligroin (10 ml.) had been added, giving 2.30 g. of (+)-2-phenyl-2-phenylmercaptopropionic acid, m.p. 88°, $[\alpha]^{30}D$ 162.0° (*c* 1.92 ethanol).

Anal. Calcd. for $C_{15}H_{14}O_2S$: C, 69.79; H, 5.46; S, 12.43. Found: C, 69.81, 69.93; H, 5.43, 5.49; S, 12.19, 12.29.

The mother liquors from the above resolution were acidified with concentrated hydrochloric acid, extracted twice with benzene, and the organic acid (21.1 g.) is isolated as before. The total acid recovery was 96%.

The recovered acid (21.1 g.) was dissolved in ethanol (29 ml.) and treated with a solution of (−)-1-phenylethylamine[14] (10.1 g.) in ethanol (29 ml.). Hot water (80 ml.) was added, and the salt collected as before. Seven recrystallizations of this salt in the manner previously described led to pure (−)-1-phenylethylammonium (−)-2-phenyl-2-phenylmercaptopropionate, 6.3 g., m. p. 154–155°, $[\alpha]^{25}D$ −204.3° (*c* 0.881 ethanol).

Anal. Calcd. for $C_{23}H_{25}O_2NS$: C, 72.90; H, 6.66. Found: C, 72.82, 72.93; H, 6.65, 6.78.

This was decomposed with hydrochloric acid in the previously described manner to produce 3.2 g. of pure (−)-2-phenyl-2-phenylmercaptopropionic acid, m.p. 87.5–88°, $[\alpha]^{26}D$ −165.3° (*c* 1.903, ethanol).

Anal. Calcd. for $C_{15}H_{14}O_2S$: C, 69.79; H, 5.46; S, 12.43. Found: C, 69.67, 69.78; H, 5.51, 5.59; S, 12.22.

(−)-2-Phenyl-2-phenylmercaptopropionyl Chloride.—(−)-2-Phenyl-2-phenylmercaptopropionic acid (1.5 g.) was heated under reflux with thionyl chloride (15 ml.) for 90 minutes, and the excess reagent removed *in vacuo* at 100°. There remained 1.6 g. (99%) of clear, amber oil, $[\alpha]^{25}D$ −47.0° (*c* 4.89, ether). In view of the observation of Levene and co-workers[16] that (−)-2-phenylpropionyl chloride underwent partial racemization on distillation, no attempt was made to purify or analyze the present product.

(+)- and (−)-2-Phenyl-2-phenylmercaptopropionamides.—The enantiomorphic 2-phenyl-2-phenylmercaptopropionic acids were converted to their amides *via* their acid chlorides in the manner previously described for the racemic acid. (+)-2-Phenyl-2-phenylmercaptopropionamide from the dextrorotatory acid existed as fine platelets, m.p. 104°, $[\alpha]^{26}D$ 104.5° (*c* 0.88, ethanol). (−)-2-Phenyl-2-phenylmercaptopropionamide from the levorotatory acid had m.p. 104° and $[\alpha]^{25}D$ −112.0° (*c* 1.797, ethanol).

Anal. Calcd. for $C_{15}H_{15}ONS$: C, 70.00; H, 5.87; N, 5.44; S, 12.44. Found: for (+)-amide: C, 70.12, 70.13; H, 5.76, 5.88; N, 5.51; S, 12.29. For (−)-amide: C, 70.04, 70.25; H, 5.89, 5.93; N, 5.42; S, 12.30.

Reductive Desulfuration of (+)- and (−)-2-Phenyl-2-phenylmercaptopropionamides.—The dextrorotatory amide (0.50 g.) was heated under reflux with Raney nickel (7 g.) in ethanol (30 ml.) for five hours. Customary isolation yielded 0.24 g. (93%) of crude product, a clear sirup which crystallized spontaneously and was optically inactive. This was recrystallized twice from a mixture of benzene (2 ml.) and ligroin (5 ml.) to produce 0.19 g. of pure 2-phenylpropionamide, m.p. 94°, mixed m.p. with the synthetic sample above 96–96.5°.

Anal. Calcd. for $C_9H_{11}ON$: C, 72.50; H, 7.44; N, 9.38. Found: C, 72.25, 72.30; H, 7.42, 7.53; N, 9.28.

(16) P. A. Levene, L. A. Mikeska and K. Passoth, *J. Biol. Chem.*, **88**, 27 (1930).

Identical results were obtained when (−)-2-phenyl-2-phenylmercaptopropionamide was desulfurated with a different sample of Raney nickel during 3.5 hours.

(−)-2-Phenylpropionamide.—2-Phenylpropionic acid (18 g.), prepared from phenylacetonitrile as described above, was resolved into the levorotatory antipode by recrystallization of its quinine salt after the method of Levene and co-workers.[16] After three recrystallizations from acetone the 11.8 g. of salt was decomposed with dilute (1:3) hydrochloric acid, resulting in 3.4 g. of optically pure (−)-2-phenylpropionic acid, $[\alpha]^{25}D$ −58.0° (*c* 1.881, 75% ethanol). Levene records −54.2° as the rotation of this substance.

Two grams of this acid was converted *via* the acid chloride into (−)-2-phenylpropionamide, prepared and isolated in the usual manner. The crude product was recrystallized twice from benzene and ligroin to give the pure product, m.p. 98°, $[\alpha]^{24}D$ −28.5° (*c* 0.808, 75% ethanol). Levene and co-workers[16] give m.p. 92°, $[\alpha]^{25}D$ −26.3° (75% ethanol) for this product.

Anal. Calcd. for $C_9H_{11}ON$: C, 72.50; H, 7.44; N, 9.38. Found: C, 72.42, 72.53; H, 7.32, 7.46; N, 9.33.

Raney Nickel with (−)-2-Phenylpropionamide.—The amide (0.35 g.) and Raney nickel (6 g.) were refluxed in ethanol (35 ml.) for five hours. The mixture was filtered, the cake rinsed with boiling ethanol, and the filtrate distilled of solvent to produce 0.28 g. (80%) of solid. Recrystallization from benzene (2.5 ml.) and ligroin (6 ml.) gave 0.23 g. of unchanged starting material, m.p. 97°, $[\alpha]^{28}D$ −28.4° (*c* 1.02, 75% ethanol).

(+)- and (−)-2-Phenyl-2-benzenesulfonylpropionamides.—(+)-2-Phenyl-2-phenylmercaptopropionamide (0.97 g.) was dissolved in acetic acid (8 ml.) and 30% hydrogen peroxide (4 ml.) added. The solution was heated on the steam-bath for 30 minutes, then an additional 4 ml. of 30% hydrogen peroxide was added. After another half-hour on the steam-bath the mixture was cooled, poured into water and the solid filtered, 0.73 g. (68%). This was recrystallized from hot acetone (14 ml.) to which boiling ligroin (30 ml.) was added, yielding 0.66 g. of solid, m.p. 181.5–182°. Another recrystallization gave the pure product, m.p. 182°, $[\alpha]^{25}D$ 59.7° (*c* 0.554, acetone).

The enantiomorphic levorotatory isomer was prepared in an identical fashion from (−)-2-phenyl-2-phenylmercaptopropionamide, m.p. 183–183.5°, $[\alpha]^{25}D$ −69.8° (*c* 0.66, acetone).

Anal. Calcd. for $C_{15}H_{15}O_3NS$: C, 62.30; H, 5.23; N, 4.84; S, 11.05. Found: for (+)-sulfone: C, 62.15, 62.17; H, 5.01, 5.13; N, 4.88; S, 10.80. For (−)-sulfone: C, 62.53; H, 5.11; S, 10.66.

Reductive Desulfuration of (+)- and (−)-2-Phenyl-2-benzenesulfonylpropionamides.—(+)-2-Phenyl-2-benzenesulfonylpropionamide (0.40 g.) and Raney nickel (8 g.) were heated in refluxing ethanol (30 ml.) for five hours. Filtration and solvent removal left 0.21 g. (100%) of clear sirup which crystallized spontaneously. Two recrystallizations, with Norit treatment during the first, from a mixture of benzene (1 ml.) and ligroin (6 ml.) gave 0.14 g. of (+)-2-phenylpropionamide, m.p. 90.5–91°, $[\alpha]^{25}D$ 22.6° (*c* 1.237, 75% ethanol). Analysis below.

A similar experiment using (−)-2-phenyl-2-benzenesulfonylpropionamide (0.47 g.) and Raney nickel (8 g.) led to 0.20 g. (83%) of crude (−)-2-phenylpropionamide, $[\alpha]^{27}D$ −17.2° (*c* 0.524, 75% ethanol). Two recrystallizations from a 1:7 mixture of benzene and ligroin gave 0.14 g. of (−)-2-phenylpropionamide of m.p. 89.5–90°, $[\alpha]^{25}D$ −21.0° (*c* 1.717, 75% ethanol).

Anal. Calcd. for $C_9H_{11}ON$: C, 72.50; H, 7.44; N, 9.38. Found: for (+)-amide: C, 72.39, 72.38; H, 7.40, 7.44; N, 9.43. For (−)-amide: C, 71.90, 72.03; H, 7.42, 7.50; N, 9.12.

A duplication of the latter experiment produced essentially identical results. On the basis of ±28.5° as the rotations of the optically pure antipodes, the present samples are 90% stereochemically homogeneous.

Ethyl (−)-2-Phenyl-2-phenylmercaptopropionate.—(−)-2-Phenyl-2-phenylmercaptopropionyl chloride (1.6 g.) and absolute ethanol (15 ml.) were heated under reflux for an hour. The mixture was cooled, poured into water, and extracted twice with benzene. The extract was washed with water, 5% sodium hydroxide solution, and water, then dried over anhydrous sodium sulfate, filtered, and the

solvent distilled, last traces *in vacuo* at 100°. There remained 1.53 g. (93%) of amber oil, $[\alpha]^{25}D$ −89.8° (*c* 3.68, ether). Because of the small quantity of material at hand, no attempt was made at distillation or analysis.

Ethyl (−)-2-Phenyl-2-benzenesulfonylpropionate.—The above product (1.53 g.) was dissolved in acetic acid (15 ml.) and treated with 30% hydrogen peroxide (6 ml.). After 30 minutes at 100° an additional 6 ml. of hydrogen peroxide was added. After another 30 minutes on the steam-bath the solution was cooled and thrown into water, and the mixture extracted twice with benzene. After being washed with water, 5% sodium hydroxide solution, and water, then dried, the extract was evaporated to leave 1.14 g. (67%) of a thick glass, $[\alpha]^{27}D$ −15.5° (*c* 2.78, ethanol). No attempt at purification was made.

Reductive Desulfuration of Ethyl 2-Phenyl-2-benzenesulfonylpropionate.—The above product (1.14 g.) and Raney nickel (10 g.) in ethanol (30 ml.) were heated under reflux for four hours. Customary processing gave 0.40 g. (63%) of ethyl (−)-2-phenylpropionate, $[\alpha]^{25}D$ −40.9° (*c* 4.24, ether). Although the quantity on hand was too small to permit ready purification, the crude product gave a fair analysis.

Anal. Calcd. for $C_{11}H_{14}O_2$: C, 74.2; H, 7.92. Found: C, 73.3; H, 7.80.

On the basis of a rotation of −51.0° for the optically pure substance,[16] the present sample is about 90% stereochemically homogeneous.

***p*-Phenylphenacyl 2-Phenyl-2-phenylmercaptopropionate.**—2-Phenyl-2-phenylmercaptopropionic acid (2.0 g.) was dissolved in ethanol (10 ml.) and neutralized to phenolphthalein with 10% sodium hydroxide solution. *p*-Phenylphenacyl bromide (2.3 g., 10% excess) was suspended in ethanol (30 ml.), and treated with the previous solution. The mixture was boiled under reflux for two hours, cooled and poured into water. The oil was extracted with benzene, and the extract washed with water, dried over anhydrous sodium sulfate and decolorized by filtration through Norit. Solvent evaporation left 3.3 g. (94%) of sirup. This was crystallized in a mixture of benzene (10 ml.) and boiling ligroin (25 ml.). Another recrystallization gave the pure material, m.p. 119–119.5°.

Anal. Calcd. for $C_{29}H_{24}O_3S$: C, 77.00; H, 5.35; S, 7.07. Found: C, 77.25, 77.13; H, 5.61, 5.58; S, 6.73.

***p*-Phenylphenacyl 2-Phenyl-2-benzenesulfonylpropionate.**—The above ester (1.0 g.) was dissolved in acetic acid (15 ml.) and treated with 30% hydrogen peroxide (4 ml.). The solution was heated on the steam-bath for 20 minutes, cooled and thrown into water. The mixture was extracted with ether, and the extract washed with water, 5% sodium hydroxide solution and water. After drying and decolorization through Norit, the solvent was distilled to yield 0.93 g. (87%) of sirup. This was crystallized from benzene (10 ml.) and ligroin (40 ml.) to produce 0.54 g. of solid, m.p. 154–156°. Another recrystallization gave the pure product, m.p. 162°.

Anal. Calcd. for $C_{29}H_{24}O_5S$: C, 72.00; H, 5.00; S, 6.61. Found: C, 72.45, 72.39; H, 5.07, 5.13; S, 6.36.

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[CONTRIBUTION FROM THE CHEMISTRY DEPARTMENT OF THE UNIVERSITY OF WISCONSIN]

Kinetics of the Thermal Decomposition of Vinyl Ethyl Ether[1]

BY ARTHUR T. BLADES AND GEORGE W. MURPHY

The thermal decomposition of vinyl ethyl ether has been studied at 497–586° in a flow system with toluene as a carrier gas. The toluene suppresses chain reactions which could otherwise result from the production of free radicals during the decomposition. Over most of the temperature range the data indicate an intramolecular decomposition directly into acetaldehyde and ethylene as the only reaction. The constants of the Arrhenius equation are in satisfactory agreement with those obtained by Wang and Winkler,[2] who studied the decomposition of the pure ether in a static system in the temperature range 377–448°. The nature of the activated state is discussed. Above 537° a secondary reaction, with a radical split as the probable primary step, begins to be evident.

The thermal decomposition of vinyl ethyl ether into ethylene and acetaldehyde was first studied by Wang and Winkler[2] using a static system in the temperature range 377 to 448°. Although the major reaction was believed to proceed through an intramolecular mechanism, the presence of free radicals was shown by the fact that vinyl ethyl ether catalyzed the decomposition of acetaldehyde.

The present research was undertaken as the first in a series of vinyl alkyl ether decomposition studies. It was hoped that attention could be focused unambiguously on the intramolecular decomposition, to the exclusion of free radical interference. To accomplish this, the decomposition was carried out in a flow system using toluene as a carrier gas; toluene is known to react readily with a large number of free radicals, forming stable molecules and the relatively inert benzyl radical. Two benzyl radicals eventually react to form dibenzyl. This technique has been extensively applied by Szwarc in the estimation of bond energies by pyrolytic methods,[3] and more recently in the determination of rate constants in the intramolecular decomposition of acetic anhydride.[4] By using a large excess of toluene, it was hoped that, although free radicals might be produced, they would be unable to cause chain decomposition of the acetaldehyde which results from the principal reaction.

Experimental

Vinyl ethyl ether (stabilized) was purchased from General Aniline and Film Corporation and redistilled on a 10-plate column (b.p. 35.2°, $n^{25}D$ 1.3740). The toluene was Merck and Company Reagent Grade and was distilled on the same column. Although some precautions were observed to obtain peroxide-free ether, the type of experiments performed did not require it. Any peroxide-generated radicals would quickly react with toluene.

The apparatus was similar to that reported by Szwarc.[5] Toluene was allowed to vaporize from a Pyrex reservoir maintained at 22.5°, while the ether was forced to pass through a fine capillary from a reservoir at 0°. In this way a mole ratio of toluene to ether of about fifty to one was maintained throughout the run. The pressure of about 2 cm. was measured on an oil mercury manometer with a magnification factor of ten.[6]

The reaction cell was a Pyrex glass tube 1.5 cm. in diameter and 20 cm. long, surrounded by an aluminum block

(1) Presented at the 119th Meeting of the American Chemical Society, Cleveland, Ohio, April, 1951.

(2) S. Wang and C. A. Winkler, *Can. J. Research*, **21B**, 97 (1943).

(3) M. Szwarc, *Chem. Revs.*, **47**, 75 (1950).

(4) M. Szwarc, *Trans. Faraday Soc.*, **47**, 269 (1951).

(5) M. Szwarc, *J. Chem. Phys.*, **17**, 431 (1949).

(6) Ostwald-Luther, "Physiko-chemische Messungen," Funfte Aufgabe, Reprinted by Dover Publications, Inc., New York, N. Y., 1943, p. 200.