time-yields of cyanocyclohexene and vinylpyridine. The space-time-yield, defined in this instance in terms of millimoles of pyridinic product per hour per 100 cc. catalyst, is in the first approximation, a measure of the reaction rate. The space-time-yields for cyanocyclohexene and vinylpyridine in run (a) were 20 and 2.2, and run (b), 75 and 4.8, respectively. Thus with a freshly activated Cr_2O_3–Al_2O_3 catalyst, in the initial two-hour period, the (C═C) group is only 9–15 times more reactive than the (C≡N) group of acrylonitrile in the Diels–Alder reaction. The effect of the catalyst is to lower the energies of activations in these reactions. These results indicate a considerable preferential catalysis of the pyridinic cyclization reaction since the reactivity of the (C≡N) group is much more nearly that of the (C═C) group in the presence of the catalyst than in the homogeneous reaction.

Acknowledgment.—The authors gratefully acknowledge a grant-in-aid from the Research Committee, Rensselaer Polytechnic Institute, and an American Cyanamid Company Research Fellowship to N. E. D.) which helped make this work possible.

TROY, NEW YORK

[CONTRIBUTION FROM THE POLYCHEMICALS DEPARTMENT, RESEARCH DIVISION, E. I. DU PONT DE NEMOURS AND COMPANY INC.]

Extensions of the Willgerodt Reaction. I

BY M. A. NAYLOR AND A. W. ANDERSON

RECEIVED MAY 25, 1953

The Willgerodt reaction has been successfully applied to certain olefins. Conditions giving high yields of propionamide and isobutyramide from propylene and isobutylene, respectively, are described. Butadiene and *n*-butylamine gave *n*-butyramide. Cyclohexene and vinylcyclohexene gave only tars. *Under certain reaction conditions,* polysulfides have been identified and are suggested as possible reaction intermediates.

Discussion

The Willgerodt reaction has been the subject of considerable laboratory work since its discovery in 1887.[1] The reaction generally involves treatment of an organic compound containing an appropriate functional group such as keto or hydroxyl, with ammonium polysulfide at elevated temperatures. Reaction results in the formation of amides containing the same carbon skeleton. Application of this reaction to aliphatic olefins and primary amines either has not been made or yields are too low to be of interest.[2]

From information in the literature, and certain work carried out in this Laboratory, it appeared that sulfur compounds were intermediates in the reaction and that compounds such as sulfides or polysulfides might be intermediates common to these reactions. Since it was known that H_2S along with organic sulfur derivatives formed when hydrocarbons were treated with sulfur and that sulfur compounds result from the action of sulfur or polysulfides on olefins, we felt that the Willgerodt reaction might be carried out on these materials.[3,4]

In attempting to carry out this reaction on propylene and isobutylene, it was found that under mild conditions (below 200°) considerable quantities of sulfuretted oils were formed. However, recycling such oils under more vigorous conditions (above 210–220°) resulted in their conversion to amide. The oils from isobutylene have been identified as mixtures of sulfides and polysulfides from which two fractions tentatively identified as diisobutyl disulfide and diisobutyl trisulfide (or mixture of isomers of these materials) have been separated. It appears that these materials may be intermediates in the reaction, particularly since we have shown them to be convertible to amides upon further processing.

We have found that, under appropriate conditions, propylene and isobutylene will react completely with aqueous ammonia and sulfur to give the corresponding amides in high yield. A complete list of the compounds examined with yields of products is given in Table I.

TABLE I

COMPOUNDS EXAMINED IN THE WILLGERODT REACTION

Compound	Product	Yield, %
Propylene	Propionamide	75
Isobutylene	Isobutyramide	70
Butadiene	*n*-Butyramide	10–20
Cyclohexene	Tar	. . .
Vinylcyclohexene	Tar	. . .
n-Butylamine	*n*-Butyramide	20

Although a number of modifications of the "ammonium polysulfide" reagent appear in the literature along with suggestions on the use of organic solvents in this reaction, it was found that appropriate mixtures of concentrated aqueous ammonia and elemental sulfur could be used quite satisfactorily. The use of specially prepared reagents was of no advantage in this work. It was

[1] (a) M. Carmack and M. A. Spielman, "Organic Reactions," Vol. III, John Wiley and Sons, Inc., New York, N. Y., 1946, p. 83; (b) L. Cavalieri, D. B. Pattison and M. Carmack, THIS JOURNAL, **67**, 1783 (1945); (c) M. Carmack and DeL. F. De Tar, *ibid.*, **68**, 2029 (1946); (d) D. B. Pattison and M. Carmack, *ibid.*, **68**, 2033 (1946); (e) J. A. King and F. H. McMillan, *ibid.*, **68**, 525, 632, 2335 (1946); (f) E. V. Brown, *et al.*, *ibid.*, **73**, 3735 (1951); (g) J. A. Blanchette and E. V. Brown, *ibid.*, **74**, 1066 (1952); (h) R. T. Gerry and E. V. Brown, *ibid.*, **75**, 740 (1953); (i) Yukawa and Kishi, *C. A.*, **46**, 7061 (1952).

[2] M. Carmack and DeL. F. DeTar, U. S. Patent 2,495,567.

[3] (a) Friedmann, *Ber.*, **49**, 1344, 1551 (1916); (b) L. E. Riudish and B. Eastman, French Patent 936,208.

[4] (a) G. F. Bloomfield, *J. Soc. Chem. Ind.*, **68**, 66 (1949); (b) R. F. Naylor, *J. Chem. Soc.*, 1532 (1947); (c) H. E. Westlake, *et al.*, THIS JOURNAL, **68**, 748 (1946); (d) F. K. Signaigo, U. S. Patent 2,402,456; (e) W. H. Hoffert and K. Wendtner, *J. Inst. Petr.*, **35**, 171 (1949); (f) E. H. Farmer and F. W. Shipley, *J. Chem. Soc.*, 1519 (1947).

also noted that if aqueous ammonia and sulfur were heated together above 200°, large amounts of sulfur dissolved and H_2S was formed.

The gross mechanism for the reaction proposed by King and McMillan seems to us to be essentially correct. In any event the initial attack must be by sulfur, and the amine enters the molecule toward the end of the reaction sequence. The structure of the group which carries the reactive function to the end of the carbon chain might be a thioepoxide function. King and McMillan have suggested the alternate addition and elimination of hydrogen sulfide as performing this phase of the reaction.[1e]

Experimental Details

All reactions were carried out in a stainless steel 500-ml. Parr hydrogenation bomb equipped with iron gaskets and an internal cooling coil. Low boiling materials were condensed and added as liquids to the cooled bomb containing the other reactants. The mixture was agitated by placing the bomb in a rocker assembly equipped with band heaters. Temperature and time cycles were not easily controlled because of the large mass of the reactor. At the higher temperatures, times as long as 45 minutes were required to reach reaction temperature. A temperature variation of ±5° was encountered. Times were measured from the moment the reactor attained the desired temperature to the time that cooling was begun. It is felt that most runs were considerably over-reacted and that at temperatures of 230–260° a reaction time of several minutes or less might have been satisfactory.

Very early in the course of this work it was found that ammonium polysulfide could be formed from aqueous ammonia and sulfur on heating. When a mixture of 32 g. of sulfur and 100 ml. of concentrated aqueous ammonia was heated at 280° for 1 hour, the pressure remained fairly constant between 130–145 atm. On cooling, the pressure dropped to zero, and the bomb contained a dark red-brown solution with about 5 g. of undissolved sulfur. The odor of H_2S was quite noticeable. This experiment led us to believe that it was not necessary to prepare the "ammonium polysulfide reagent" described in the literature. In all of our subsequent work mixtures of elemental sulfur and aqueous ammonia were used directly.

Three general methods for isolation of the products were employed, the exact one depending upon the characteristics of the product. Direct distillation of the reaction mixture, crystallization from the reaction liquors or continuous extraction of the aqueous reaction liquors with ether or benzene served for the reaction products reported here. It was necessary to use a wide-bore condenser during continuous extraction with these systems since considerable quantities of ammonium hydrosulfide sublimed into the condenser and caused plugging. The tubular extractors were operated for 21 hours when used.

Isobutylene Reaction.—A mixture of 64 g. (2 moles) of sulfur and 150 ml. (2.22 moles) of aqueous ammonia was placed in the bomb and cooled to −30°. Isobutylene was then condensed and 28 g. (0.5 mole) was added to the bomb. The bomb was closed, and the reaction was carried out under the conditions and with the results given on the first line of Table III. This amount of isobutyramide was recovered by cooling the reaction mixture to 10–20° and by allowing the amide to crystallize out. The tendency for isobutyramide to sublime under mild conditions made distillation impractical.

The H_2S generated caused an autogenous pressure rise increasing with increasing temperature. The maximum pressure reached is given in Table III. On cooling to room temperature at the end of the reaction, the pressure was always in the 13.5–27 atm. range. The H_2S was bled off through a caustic trap.

Effect of Temperature on Reaction with Isobutylene.—The influence of temperature was studied briefly. A considerable amount of water-insoluble oil was formed at the expense of amide at 150–200°. Thus 20–30 g. of oil appeared when the reaction was carried out at 160–180°, while 7–13 g. g. was formed at 220°. Fractionation of 120 g. of these oils through an 18-inch helix packed column gave the results in Table II.

TABLE II

FRACTIONATION OF OIL FROM WILLGERODT REACTION ON ISOBUTYLENE (PRESS. 0.5–1 MM.)

Fraction	Boiling range, °C.	Yield, g.	$n^{20}{}_D$	$d^{20}{}_4$
1	27–30	20.2	1.4878	0.951
2	30–46	35.8	1.5120	...
3	44–47	17.3	1.5200	1.022
4	47–52	14.6	1.5200	...
Residue	...	26.3	1.5200	...

Fraction 1 was characterized using the following physical constants for diisobutyl disulfide: b.p. 84° (3 mm.), $n^{20}{}_D$ 1.4867, $d^{20}{}_4$ 0.928.[5]

Anal. Calcd. for $C_8H_{18}S_2$: C, 53.9; H, 10.2; S, 35.9. Found: C, 53.6; H, 10.3; S, 35.3.

Fraction 3 was compared with diisobutyl trisulfide as follows. Molar refraction calcd. using 8.11 as the atomic refractivity of sulfur, M_R 61.3; M_R of fraction 3, 62.4.

Anal. Calcd. for $C_8H_{18}S_3$: C, 45.6; H, 8.6; S, 45.7. Found: C, 46.2; 8.9; S, 45.1.

In order to show that these polysulfides were possible intermediates in the Willgerodt reaction, 30 g. of the unfractionated material was treated with 64 g. of sulfur in 150 ml. of aqueous ammonia for 2 hours at 240°. Filtration of the cold reaction product gave 20 g. of crystals which were identified as isobutyramide by mixed melting point (126°) after several recrystallizations from ethyl acetate and diethyl ether.

Effect of Recycling Liquors on Reaction with Isobutylene.—As we have mentioned before, the nature of our equipment restricted our latitude in varying the time of reaction. At relatively high temperatures, amide was formed rapidly, but in lower yields. At temperatures where we believed our yields might be high, the reaction was slow. Consequently, we decided to recycle the mother liquor (after removing the amide which had crystallized from the reaction mixture) in an attempt to improve our yield to amide. An amount of isobutylene (28 g., 0.5 mole), sulfur (32 g., 1 mole) and anhydrous ammonia (10 g., 0.59 mole) was added to these mother liquors for recycle which was roughly equivalent to that used up if the reaction were quantitative to isobutyramide or intermediates convertible thereto. Enough aqueous ammonia was also added to make up for mechanical losses during handling. The yield after each recycle was calculated on the basis of the increment of olefin added. The important point to note in Table III is that yields of amide were relatively constant after the first recycle. The amide was recovered in each cycle by crystallization followed by filtration. This isolation technique worked well where the reaction was reasonably complete in each cycle.

TABLE III

EFFECT OF RECYCLING LIQUORS ON YIELD OF ISOBUTYRAMIDE FROM ISOBUTYLENE

	4 hr., 220°, max. press. 157 atm. Yield		2 hr., 250°, max. press. 270 atm. Yield	
Conditions	g.	%	g.	%
Initial reacn.	20.5	47	13.0	30
1st recycle	30.4	70	30.9	71
2nd recycle	34.0	78	31.0	73
3rd recycle	30.3	69	..	..

Continuous extraction with ether or benzene was used in those cases where yields were low; however, distillation of the extract was complicated by the tendency of isobutyramide to sublime. If reaction temperatures were too low, unreacted sulfur crystallized and complicated isolation of amide.

Crude isobutyramide filtered directly from the reaction mix was purified by several recrystallizations from ethyl acetate or diethyl ether. Sublimation of the amide after one recrystallization was an effective method for purification, giving a product with m.p. 126°, lit. 128°, mixed m.p. 126°.

---

(5) A. I. Vogel and D. M. Cowan, *J. Chem. Soc.*, 10 (1943).

Anal. Calcd. for C_4H_9NO: N, 16.08. Found: N, 16.21, 16.09.

The product was further identified by vapor-phase dehydration over alumina–silica gel (Sovabead catalyst from Socony–Vacuum Oil Company, Paulsboro, N. J.) at 425°. Excellent yields of isobutyronitrile (90%) were obtained which on drying followed by fractionation gave nitrile, b.p. 101–103°, $n^{20}\mathrm{D}$ 1.3712; lit. b.p. 103°, $n^{20}\mathrm{D}$ 1.3713.[6] Infrared spectra also were used to identify the amide and nitrile.

Propylene Reaction.—A mixture of 64 g. of sulfur and 150 ml. of aqueous ammonia was placed in the bomb and cooled to −50°. Condensed propylene (21 g.) was then added, and the mixture was heated and rocked for the desired period of time. When the mother liquors were recycled, as described in the section on the isobutylene reaction, make-up consisting of 21 g. of propylene, 23 g. of sulfur, 10 g. of anhydrous ammonia and enough aqueous ammonia to keep the liquid volume at 150 ml. was used.

When the reaction was conducted at 170–190°, the initial pressure rose to 54.5–64 atm.; however, after 10–15 minutes, the pressure dropped to 37.5–51 atm. and remained there for over 30 minutes. This indicated very little H_2S formation and consequently low conversion to amide. It seems likely that propylene was converted to sulfuretted intermediates, but that these are only slowly converted to amide at these temperatures. On raising the temperature to 210°, reaction set in, and the pressure rose from about 64 atm. to *122–136* atm. in *about 1 hour. At 250° the* reaction gave about the same yields as at 210°, but the initial pressure on reaching reaction temperature was 170 atm. and increased to 204–230 atm. in 0.5–1 hour.

Propionamide does not tend to sublime and did not crystallize from the reaction mixture like isobutyramide. Continuous extraction (21 hours) was used to isolate this product. Diethyl ether, while not the best solvent for propionamide, gave the cleanest extraction and left most of the excess sulfur in the aqueous layer. Benzene, carbon tetrachloride and ethyl acetate were tested but proved to be less selective toward the amide in this system. When the reaction was carried out under conditions giving high conversions to amide, direct distillation of the reaction product after a flash distillation of the water proved to be an excellent method for isolation. Propionamide is only slightly attacked by the excess sulfur during vacuum distillation at 100–140°.

The product from continuous ether extraction of the reaction mixture gave a forerun on distillation boiling from 40–100°. This material contained an organic and a water layer. Drying the almost colorless organic layer produced a product of the following properties: $n^{20}\mathrm{D}$ 1.4556, % S 29.2. Diisopropyl sulfide has $n^{20}\mathrm{D}$ 1.439, % S 26.9.[5] The aqueous layer from this forerun contained some propionic acid identified as follows: $n^{20}\mathrm{D}$ 1.3860, d^{20}_4 1.010, equiv. wt. 78. Propionic acid has $n^{20}\mathrm{D}$ 1.3874, d^{20}_4 0.992, equiv. wt. 74.

Propionamide was purified by fractionation or recrystallization yielding a white crystalline product with a b.p. 136–137° at 45–50 mm. and 212–214° at 760 mm., m.p. 76°, mixed m.p. 76°.

Anal. Calcd. for C_3H_7NO: N, 19.16. Found: N, 19.20.

Recycling the mother liquors from ether extraction, as described in the section on the isobutylene reaction, gave yields of 60–80% of pure product after the third recycle.

The propionamide was dehydrated to propionitrile under the same conditions used for the preparation of isobutyronitrile. This product was obtained in an 85% yield, b.p. 95.5–96.5°, $n^{20}\mathrm{D}$ 1.3660; lit. for propionitrile b.p. 97°, $n^{20}\mathrm{D}$ 1.3662.[6]

The propionitrile made in this way was partially dehydrogenated by known methods to acrylonitrile.[7a,b] The product of the dehydrogenation absorbed bromine readily at 25°. Fractional distillation gave a material with a b.p. 108–110° at (25 mm.), $n^{20}\mathrm{D}$ 1.5410, d^{20}_4 2.09; lit. for α,β-dibromopropionitrile, b.p. 106–107° (22 mm.), $n^{20}\mathrm{D}$ 1.5452, d^{20}_4 2.140.[8]

This work indicates that both saturated and unsaturated nitriles are readily available from the simple olefins.

Reaction with Butadiene.—This reaction was carried out with 27 g. (0.5 mole) of butadiene, 64 g. of sulfur (2 moles), 150 ml. of aqueous ammonia (2.2 moles) at 200° for 2 hours, giving a pressure rise from 47–82 atm. A yield of 7 g. of crude product was obtained from ether after 20 hours of continuous extraction. After four recrystallizations and a charcoal treatment in ethyl acetate, 4 g. of pure *n*-butyramide was isolated, m.p. 113°, mixed m.p. 112.5°. The butadiene was 99% pure by infrared analysis.

Anal. Calcd. for C_4H_9NO: N, 16.08. Found: N, 16.01.

***n*-Butylamine Reaction.**—A mixture with 0.5 mole of *n*-butylamine was treated as above giving 7.0 g. of *n*-butyramide on direct filtration of the reaction liquor after evaporation to one-half the original volume. After three recrystallizations from ethyl acetate, the product gave m.p. 112–113°, mixed m.p. 112°.

Anal. Calcd. for C_4H_9NO: N, 16.08. Found: N, 16.10.

Cyclohexene Reaction.—A mixture of 41 g. of cyclohexene was treated as above at 220° for 4 hours. The maximum pressure was 150 atm. A black tar with a phenolic odor separated from the reaction mixture. A few efforts to obtain identifiable products from this mixture failed.

Vinylcyclohexene Reaction.—Vinylcyclohexene (54 g.) was treated as above for 2 hours at 200°. A sticky tar separated from the reaction mixture. Continuous extraction for 23 hours with ether removed only a small quantity of non-crystallizable tar.

Acknowledgment.—The authors wish to thank Dr. C. F. Hammer for the infrared spectra measurements and Mr. W. P. Pickhardt for the elemental analyses reported here.

WILMINGTON, DEL.

---

[6] L. M. Peters, *et al.*, *Ind. Eng. Chem.*, **40**, 2046 (1948); "Org. Syntheses," **25**, 61 (1945).

[7] (a) N. Brown, U. S. Patent 2,554,482; (b) D. J. Loder, U. S. Patent 2,554,484.

[8] C. Moureu and R. L. Brown, *Bull. soc. chim. France*, [4] **27**, 904 (1949).