

THE PREPARATION OF CYCLOBUTANE

JAMES CASON AND RICHARD L. WAY

Received July 16, 1948

Although Willstätter and Bruce (1) prepared cyclobutane as early as 1907 this hydrocarbon has remained so difficultly accessible that accumulation of physical data concerning it has lagged behind that available for the other low molecular weight cycloalkanes. In order to supply material for further study of cyclobutane in this laboratory¹ we have undertaken the development of improved methods for its preparation.

Since cyclopropane is easily prepared in high yield (2) by the Wurtz reaction on trimethylene bromide, it might be expected that cyclobutane could be readily prepared from tetramethylene bromide. Demjanow (3) has reported, however, that the Wurtz reaction on tetramethylene bromide, using zinc in ethanol, leads to *n*-butyl bromide, while Hamonet (4) obtained *n*-butane. Recently, Keilin (5) has studied this reaction under a variety of conditions, including those found best for preparation of cyclopropane, and obtained no cyclobutane under any conditions used. The product was either butane or a mixture of butane and unsaturated material.

The original successful synthesis of Willstätter (1, 6) utilized cyclobutanecarboxylic acid as starting material. This acid was converted to the amide which was in turn converted to cyclobutylamine by the Hoffman hypohalite reaction. Exhaustive methylation and pyrolysis of the quaternary hydroxide gave cyclobutene mixed with 1,3-butadiene. Bromination of this mixture was followed by separation of the bromides, and cyclobutene was regenerated from the dibromide. Careful hydrogenation gave cyclobutane. This lengthy procedure was necessary for elimination of the carboxyl group, for Perkin and Colman (7) had found that decarboxylation by heating the calcium salt gives ethylene.² Although Willstätter's method starts with a relatively inaccessible material and gives a very low over-all yield, it has remained the principal source of cyclobutane. Heisig (8) has been able to improve the yield by using the Curtius acid azide rearrangement for preparation of the amine. The only other method which has yielded any cyclobutane is photolysis of cyclopentanone (9), and this process seems hardly practical for production of appreciable amounts of the hydrocarbon. The elaborate apparatus described in the patent was claimed to produce about 0.001 mole of cyclobutane per hour.

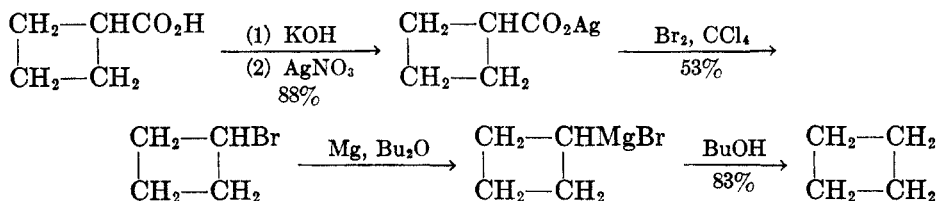
The present investigation was first directed towards the Wurtz reaction on tetramethylene bromide, and it has been found that when this reaction is carried

¹ These investigations will be reported in another journal by Professor K. S. Pitzer and co-workers.

² In an experiment by Mr. Donald Orth, of this laboratory, it was found that decarboxylation with copper chromite in boiling quinoline also leads to no products condensable at -70° . The evolved gases gave a precipitate with barium hydroxide and reduced permanganate.

out with sodium in boiling toluene a 7% yield of cyclobutane may be obtained. There was also obtained a similar amount of butane, which boils only about 12° below cyclobutane, and the necessity for separating this mixture detracts from the utility of the method. Since unsaturation tests on the butane fraction were negative it would appear that protons for reduction to butane must have been obtained from the solvent; so the reaction was run in benzene, in hopes that butane formation would be reduced by the lesser tendency of benzene to donate protons. Unfortunately, a contrary result was obtained; the yield of cyclobutane became nearly zero even when the concentrations in benzene were reduced to one-fourth those used in toluene. This difference might be ascribed to the fact that sodium is solid in boiling benzene and molten in boiling toluene; however, it seems more probable that the temperature coefficient of the reaction leading to cyclobutane is greater than those of competing reactions leading to other products. The reaction has not been studied in higher-boiling solvents, for at this stage of the investigation there was developed the method described below, which yields cyclobutane free of butane.

Pure cyclobutane may be obtained in quantities of a mole or more by the illustrated sequence of reactions.



The over-all yield from cyclobutanecarboxylic acid is about 39%. Preparation of this starting material has been studied and will be reported in a later publication.

The reaction of a silver salt with bromine in anhydrous medium, as developed by Hunsdiecker (10) and applied to numerous compounds (11), was successful with silver cyclobutanecarboxylate after proper conditions had been discovered. When the reaction was carried out by adding bromine to a suspension of the silver salt in boiling carbon tetrachloride, no cyclobutyl bromide could be isolated. The entire product consisted of higher-boiling material. When the reaction was carried out by adding the silver salt to a carbon tetrachloride solution of bromine at -25°, considerable high-boiling material was again obtained, but there was also isolated the indicated yield of cyclobutyl bromide, b.p. 108.2-108.3° (760 mm.).

The high-boiling material from both the lower and higher temperature reactions was found to consist of two fractions. The lower-boiling of the two fractions proved to be cyclobutyl cyclobutanecarboxylate, the ester which would result from reaction of the silver salt with cyclobutyl bromide. Such an ester is a recognized by-product of the silver salt reaction with one molar equivalent of bromine, but in the other instances studied the ester has been obtained in smaller amount. The larger amount of ester obtained in the present instance may be a

result of the bromide being secondary, but it may also be a result of the fact that the intermediate in the reaction (presumably RCO_2Br , *cf.* ref. 11) lost carbon dioxide readily, even at -25° , after a short induction period. Thus, bromide was present as the last of the silver salt was added, and there was opportunity for the two to react. There is no proof, however, that the ester is formed by this mechanism. It may be formed by way of a different complex between the silver salt and bromine (11).

The higher-boiling by-product, present in smaller amount in the low-temperature reaction, proved to be of high density and to contain bromine.³ The analysis and molecular refraction are in reasonable agreement with the formula, $\text{C}_4\text{H}_7\text{Br}_3$; hence, the four-carbon ring appears to have been opened by bromine unless there was prior rearrangement to a three-carbon ring. Determination of the structure of the tribromide should throw some light on this matter, but it has not been further investigated by us since our present objective is preparation of cyclobutane.

Conversion of cyclobutyl bromide to the hydrocarbon by way of the Grignard reagent offered no difficulties when the reaction was run in di-*n*-butyl ether, and the Grignard complex was decomposed with *n*-butyl alcohol. Use of these reagents permitted easy separation of the low-boiling product, which was passed through a sulfuric acid wash and collected in a cold trap. Distillation through a four-foot column showed the condensate to consist almost entirely of cyclobutane, b.p. $11.15\text{--}11.35^\circ$ (760 mm.)

EXPERIMENTAL

Microanalyses are by C. W. Koch and V. H. Tashinian. Boiling points are corrected with an accuracy of about 0.3° . Reduced pressures of 5 mm. or more were measured with a Zimmerli gage, those less than 5 mm. were measured with a tilting McLeod gage.

Cyclobutyl bromide. A mixture of 100 g. (1 mole) of cyclobutanecarboxylic acid and 270 ml. of water was titrated to a phenolphthalein end-point with 2 *N* potassium hydroxide. This solution was stirred vigorously while a solution of 172 g. (1.01 mole) of silver nitrate in 540 ml. of water was added during ten to fifteen minutes. The thick mixture was stirred an additional fifteen minutes, then the silver cyclobutanecarboxylate was collected by suction filtration. The salt was stirred well with 800 ml. of water, collected again, and washed with methanol. After drying overnight at atmospheric pressure at about 100° , the salt was ground, dried overnight in a vacuum oven at $95\text{--}100^\circ$ (wt. 181.5 g., 87.7% yield), placed in the flask in which it was used for the next reaction, and again dried overnight in the vacuum oven at $95\text{--}100^\circ$.

To a flask equipped with mercury-sealed stirrer was added 560 ml. of carbon tetrachloride (dried over phosphorus pentoxide), and 50 ml. of carbon tetrachloride was distilled in order to dry the flask thoroughly utilizing the azeotrope with water. The system was protected with a drying tube, and after addition of 85.2 g. (0.534 mole) of bromine (dried over phosphorus pentoxide), the mixture was cooled to -25° with stirring. The silver salt (111 g., 0.534 mole) was added during about fifty minutes through a wide rubber connection from the flask in which it had been dried. After an induction period of five to twenty minutes vigorous evolution of carbon dioxide set in, and continued as the remainder of the silver salt

³ Prior to our isolation of this compound, it was isolated in the laboratory of Professor E. R. Buchman, at California Institute of Technology. Our high-boiling fractions were worked up after Professor Buchman had advised us in a private communication that they had obtained the tribromide as a chief product of the reaction.

was added. Evolution of carbon dioxide was accompanied by evolution of heat, but the temperature was easily maintained at -25 to -20° with a Dry-Ice-acetone bath. After addition was complete the mixture was stirred an additional brief period until gas evolution became slow, then was allowed to warm to room temperature with stirring. When gas evolution had ceased, the silver bromide was removed and washed with carbon tetrachloride. The filtrate was washed with 2 *N* sodium hydroxide and water, then dried over calcium chloride. The combined alkaline extracts from a total of 2.6 moles of silver salt yielded only 2.2 g. of acidic material.

The carbon tetrachloride solution was flash-distilled through a 1-meter column packed with glass helices and equipped with heated jacket and partial reflux head. During flash distillation, the mole fraction of cyclobutyl bromide in the pot was kept below 0.2, and carbon tetrachloride was collected at 76.9° . After addition was complete, removal of solvent was continued, then an intermediate fraction was collected, b.p. 76.9 – 108.2° , wt. 7.9 g. Cyclobutyl bromide was collected at 108.2 – 108.3° (760 mm.), n_D^{20} 1.4801, d_4^{20} 1.434, MR_D^{25} 26.75 (calc'd 26.72). The weight of this fraction was 36.0 g. (50%), and there was 15.0 g. of distillation residue. By redistilling the intermediate fractions from several runs, and stripping the residues in a vacuum, the total yield was raised to 53%. The same yield was obtained in a 1.9-mole run. Perkin (12) reported the b.p. of cyclobutyl bromide as 104° .

By-products from cyclobutyl bromide preparation. The distillation residues from three runs in which a total of 2.6 moles of silver salt was processed were distilled in a vacuum to yield the following fractions: (a) wt. 9.0 g., b.p. 34.0 – 35.0° (50 mm.); (b) 4.8 g., b.p. 35.0° (50 mm.) – 88.0° (16 mm.); (c) 25.3 g., b.p. 88.0 – 90.5° (16 mm.); (d) 1.3 g., b.p. 67.5 – 94.0° (5 mm.); (e) 16.7 g., b.p. 94.0 – 96.0° (5 mm.); residue 8.9 g. Fraction (a) is cyclobutyl bromide, while fractions (b) and (d) are intermediate fractions. Fraction (c) is *cyclobutyl cyclobutanecarboxylate*, and for analysis there was used a center cut of this fraction, b.p. 89.0 – 89.1° (16 mm.) n_D^{20} 1.4542, d_4^{20} 0.995.

Anal. Calc'd for $C_8H_{14}O_2$: C, 70.10; H, 9.15; MR, 41.98.

Found: C, 69.80; H, 9.11; MR_D^{25} , 41.96.

Fraction (e) is the *tribromobutane* first obtained by Buchman. For analysis there was used a center cut, b.p. 76.0 – 76.3° (1.9 mm.), n_D^{21} 1.5606, d_4^{21} 2.124.

Anal. Calc'd for $C_4H_7Br_3$: C, 16.30; H, 2.38; Br, 81.31; MR, 44.05.

Found: C, 18.10, 18.12; H, 2.70, 2.83; Br, 78.18; MR_D^{25} , 44.00.

Although the tribromide boiled over a narrow range, and refractionation failed to indicate constituents of different boiling point, "streaming effect" was noted in the receiver throughout distillation of this fraction, and the elementary analysis showed the presence of a small amount of a substance containing much less bromine and some oxygen. This was probably cyclobutyl 1-bromocyclobutane-1-carboxylate.

From a run in which the bromine was added to a stirred suspension of the silver salt in boiling carbon tetrachloride, no cyclobutyl bromide was obtained. The high-boiling product contained a ratio of 3.1 g. of ester to 4.0 g. of tribromide.

Cyclobutane. (A) *From tetramethylene bromide.* To 100 g. (4.35 atoms) of sodium, stirred vigorously under 465 ml. of dry, sulfur-free toluene, heated to boiling, there was added during ninety minutes 280 g. (1.3 mole) of tetramethylene bromide. The toluene was kept boiling, and the reaction was carried out in an atmosphere of nitrogen. Evolved gases which passed a water-cooled condenser were bubbled through concentrated sulfuric acid and collected in a trap cooled with Dry Ice and acetone. The trap was protected by a drying tube, and the system was thoroughly dried in a stream of nitrogen before the reaction was started. After bromide addition was complete, the reaction mixture was heated under reflux until gas evolution ceased (about thirty minutes). The material collected in the cold trap (13.3 g.) was fractionally distilled through a 4-foot vacuum-jacketed column⁴

⁴ We are indebted to Professor K. S. Pitzer for the use of this column, which was constructed in his laboratory, and to Mr. A. Webb for assistance in its operation. The boiling

consisting of a 6 mm. tube, and equipped with partial reflux head and vapor take-off. The following fractions were obtained at 760 mm. pressure: (a) *n*-butane, wt. 4.7 g., b.p. $-2.0-0.0^{\circ}$; (b) intermediate, wt. 2.5 g., b.p. $0.0-9.0^{\circ}$; (c) cyclobutane, wt. 5.1 g., b.p. $9.0-12.0^{\circ}$; residue, 1.0 g. The yield of cyclobutane was 7%, and a center cut obtained on redistillation, wt., 2.2 g., b.p. $11.0-11.3^{\circ}$, gave an infra-red spectrum¹ nearly identical with that shown by the sample described below. A b.p. of 12.5° (760 mm.) is calculated from Heisig's (8) vapor pressure data.

When an identical reaction was carried out in boiling benzene, after the sodium had been powdered under toluene, there was obtained from one mole of tetramethylene bromide only 5.4 g. of material in the cold trap, and fractional distillation gave 2.2 g. of fore-run, 2.2 g. of cyclobutane, b.p. $8.8-11.1^{\circ}$, and 1.0 g. of residue.

When a third run was made, using four times the volume of benzene used in the previous run, only 3.0 g. of material was collected in the cold trap, and there was no fraction boiling above 10.5° . Since it was felt possible that there was some difficulty in separating the cyclobutane from the benzene by simply heating under reflux, excess sodium was destroyed with methanol and the mixture was heated under a 3-foot packed column until benzene reached the top of the column, but no further gas was evolved.

(B) *From cyclobutyl bromide.* A flask arranged for carrying out a Grignard reaction in an atmosphere of nitrogen was attached to a gas absorption train similar to that described above, and in the flask were placed 100 ml. of absolute di-*n*-butyl ether,⁵ 4.86 g. of magnesium turnings, and 2 g. of cyclobutyl bromide. After the reaction had been started by stirring the mixture for a few minutes at about 50° , there was added during two hours a solution of 24.9 g. of cyclobutyl bromide in 100 ml. of absolute di-*n*-butyl ether, the temperature being maintained at $40-50^{\circ}$. After addition was complete, the mixture was stirred an additional fifteen minutes, then treated with 40 ml. of *n*-butyl alcohol during about thirty minutes while the temperature was kept below 50° by external cooling. The homogeneous stirred mixture was then slowly warmed under reflux at such a rate that none of the evolved gas passed the cold trap, and the solution was finally heated to boiling until no more gas was evolved (total heating time about ninety minutes). Fractionation of the condensed gas through the 4-foot column gave 0.8 g. of fore-run, b.p. $5.5-11.00^{\circ}$, and 9.3 g. (83% yield) of cyclobutane, b.p. $11.0-11.35^{\circ}$.

From a similar run using 1.2 mole of cyclobutyl bromide, there was obtained 2.4 g. of fore-run, b.p. $8.5-11.15^{\circ}$, and 49.5 g. (77% yield) of cyclobutane, b.p. $11.15-11.35^{\circ}$.

SUMMARY

There has been developed a new method for preparing cyclobutane from cyclobutanecarboxylic acid. Silver cyclobutanecarboxylate was converted to cyclobutyl bromide, which was in turn converted to cyclobutane by way of the Grignard reagent.

Cyclobutane has also been obtained in 7% yield by means of the Wurtz reaction on tetramethylene bromide.

BERKELEY, CALIFORNIA

point was measured with a thermocouple inserted in a glass well containing oil, which was inside the cooling head; so the b.p.'s reported for the low-temperature distillations may be somewhat low.

⁵ Di-*n*-butyl ether appears to form an azeotrope with *n*-butyl alcohol, for a sample of the ether which had been distilled through a half-meter column and collected over a range of 0.5° contained considerable quantities of alcohol. Evolution of gas ceased only after standing over sodium for several weeks. This behavior is not explained by any reported azeotrope of di-*n*-butyl ether [Horsley, *Anal. Chem.*, **19**, 508 (1947)].

REFERENCES

- (1) WILLSTÄTTER AND BRUCE, *Ber.*, **40**, 3979 (1907).
- (2) HASS, McBEE, HINDS, AND GLUESENKAMP, *J. Ind. Eng. Chem.*, **28**, 1178 (1936).
- (3) DEMJANOW, *Ber.*, **28**, 22 (1895).
- (4) HAMONET, *Compt. rend.*, **132**, 789 (1901).
- (5) KEILIN, M.S. Thesis, California Inst. of Technology (1945).
- (6) WILLSTÄTTER AND SCHMADEL, *Ber.*, **38**, 1992 (1905).
- (7) PERKIN AND COLMAN, *J. Chem. Soc.*, **51**, 228 (1887).
- (8) HEISIG, *J. Am. Chem. Soc.*, **63**, 1698 (1941).
- (9) KISTIAKOWSKY AND BENSON, U. S. Patent 2,414,880 (1947).
- (10) HUNSDIECKER AND HUNSDIECKER, *Ber.*, **75**, 291 (1942).
- (11) KLEINBERG, *Chem. Rev.*, **40**, 381 (1947).
- (12) PERKIN, *J. Chem. Soc.*, **65**, 950 (1894).