probably due to the insolubility of an intermediate in the saturated hydrocarbons; complexing solvents are themselves known to decompose I (M = $PdBr_2$).

It was also found that in favored cases the tetraphenylcyclobutadiene group could replace a cyclopentadienyl group. Thus cobaltocene (another compound which readily abstracts covalently-bound halogens[14]) reacted with I (M = $PdBr_2$) in refluxing xylene to give a 12% yield of (π-cyclopentadienyl)-(π-tetraphenylcyclobutadiene)-cobalt (IV). This was identical with a sample prepared from cobaltocene and diphenylacetylene,[15] and this ligand transfer reaction provides additional confirmation for the structure of IV.[16]

The extension of this work to other systems and reactions in which cyclopentadienyl groups can also be transferred from one metal to another will be reported later.

Acknowledgment.—We thank the National Research Council of Canada and the Research Corporation of New York for supporting this work.

(14) S. Katz, J. F. Weiher and A. F. Voight, *J. Am. Chem. Soc.*, **80**, 6459 (1958).

(15) A. K. Nakamura and N. Hagihara, *Bull. Chem. Soc. Japan*, **34**, 452 (1961); J. L. Boston, D. W. A. Sharp and G. Wilkinson, *J. Chem. Soc.*, 3488 (1962).

(16) It is conceivable at least that this reaction too may go *via* primary dissociation of tetraphenylcyclobutadiene into two diphenylacetylenes which then react with the cobaltocene. However, as there is as yet no definite evidence for this process occurring we prefer to regard this too as a direct ligand replacement reaction.

DEPARTMENT OF CHEMISTRY
MCMASTER UNIVERSITY
HAMILTON, ONTARIO, CANADA

P. M. MAITLIS
M. L. GAMES

RECEIVED APRIL 29, 1963

Reaction of Phosphorus Compounds. VI. Kinetics and Mechanism of the Wittig Reaction

Sir:

Our recent work on the Wittig reaction of resonance-stabilized α-halomethylenephosphoranes[1] has prompted a thorough examination of the mechanism of this reaction. The Wittig reaction, represented by the following sequence, has been qualitatively described in mechanistic terms.[1b,2-4]

$$R_3P{=}CHR' + R''CHO \longrightarrow \underset{\underset{O-CHR''}{|}}{R_3\overset{\oplus}{P}-CHR'} \longrightarrow R_3P{\longrightarrow}O + R'CH{=}CHR''$$

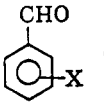
I

Four mechanistic possibilities were considered at the outset of this study: (a) irreversible formation of betaine (I) with subsequent slow decomposition of the betaine, either *via* a four-membered ring intermediate or synchronously, to phosphine oxide and olefin; (b) rate-determining, irreversible formation of the betaine and rapid decomposition of betaine to products; (c) rapid, reversible formation of betaine with subsequent rate-controlling formation of products; (d) slow, reversible formation of betaine and rapid decomposition of betaine to phosphine oxide and olefin.

We have studied the kinetics of the reaction of carbomethoxymethylenetriphenylphosphorane with several aldehydes in benzene at 25°. The reaction was found to be second-order over-all; first-order in each of aldehyde and ylid. These data are reported in Table I.

The observed rate constant for olefin formation in the reaction of the above ylid with *p*-methoxybenzaldehyde was $7.00 \pm 0.13 \times 10^{-5}$ l./mole-sec. Within experimental error the rate of disappearance of ylid is the same as the rate of formation of olefin.

TABLE I

$(C_6H_5)_3P{=}CHCO_2CH_3$ +  (Benzene, 25°)

Aldehyde	$k_{obs.}$ (l./mole-sec.)
p-Methoxybenzaldehyde	$7.10 \pm 0.00 \times 10^{-5}$
p-Methylbenzaldehyde	$2.15 \pm 0.03 \times 10^{-4}$
Benzaldehyde	$9.62 \pm 0.02 \times 10^{-4}$
m-Chlorobenzaldehyde	$1.20 \pm 0.04 \times 10^{-2}$
p-Nitrobenzaldehyde	$1.07 \pm 0.00 \times 10^{-1}$

The enhanced rate with electron-withdrawing substituents can be interpreted in terms of any of the previously mentioned mechanisms. The rate expression for mechanism (a), however, demands different rates of disappearance of ylid and of formation of olefin. Since we have observed these to be identical, mechanism (a) may be eliminated. These quantitative results are in accord with the qualitative observations of Johnson and LaCount,[5] who were unable to isolate a betaine intermediate in the reactions of stable ylids. If mechanism (a) were operative, as it most likely is in the reactions of unstable ylids,[4] the betaine intermediate should be isolable.

It is not possible to choose among the three remaining mechanistic possibilities on the basis of kinetic data alone. Consequently, the demonstration of reversibility or irreversibilty of betaine formation becomes very important in the elucidation of the mechanism of the Wittig reaction. The ring opening of *trans*-ethyl phenylglycidate (II) with tributylphosphine was studied in order to arrive at the betaine (III) *via* a different route. Boskin and Denny[6] have shown that the attack of tributylphosphine on *cis*- and *trans*-2-butene oxide occurs mainly at carbon. Further, it has been shown that nucleophilic attack in the ring opening of ethyl phenylglycidate occurs at the α carbon atom.[7]

$$Bu_3P + \underset{\text{II}}{C_6H_5\overset{O}{\diagup\diagdown}CHCO_2Et} \longrightarrow \underset{\underset{O-CHC_6H_5}{|}}{Bu_3\overset{\oplus}{P}-CHCO_2Et} \rightleftharpoons \underset{\text{IV}}{Bu_3P{=}CHCO_2Et} + C_6H_5CHO$$

III

$$Bu_3P{\longrightarrow}O + C_6H_5CH{=}CHCO_2Et$$

If betaine formation in the Wittig reaction is reversible, evidence for reversibility may be obtained by trapping the ylid (IV) with an aldehyde more reactive than benzaldehyde.

Tributylphosphine was allowed to react with *trans*-ethyl phenylglycidate in the presence of a three-molar excess of *m*-chlorobenzaldehyde in refluxing ethanol. Under these conditions the reaction was essentially complete in 20 hr. V.p.c. analysis of the products of the reaction showed the presence of *m*-chlorobenzaldehyde, benzaldehyde, ethyl cinnamate and ethyl *m*-chlorocinnamate in the following area proportions: benzaldehyde, 1.0; *m*-chlorobenzaldehyde, 6.5; ethyl cinnamate, 1.3; ethyl *m*-chlorocinnamate, 1.1. Each of the products was isolated with preparative v.p.c. The aldehydes were oxidized to the corresponding benzoic acids and

(1) (a) A. J. Speziale and K. W. Ratts, *J. Org. Chem.*, **28**, 465 (1963); (b) A. J. Speziale and K. W. Ratts; to be published.

(2) H. O. House and G. H. Rasmusson, *J. Org. Chem.*, **26**, 1278 (1961).

(3) H. J. Bestmann and O. Kratzer, *Ber.*, **95**, 1894 (1962).

(4) G. Wittig, H. Weizmann and M. Schlosser, *ibid.*, **94**, 676 (1961).

(5) A. W. Johnson and R. B. LaCount, *Tetrahedron*, **9**, 130 (1960).

(6) M. J. Boskin and D. B. Denney, *Chem. Ind.*, 330 (1959).

(7) R. E. Parker and N. S. Isaacs, *Chem. Rev.*, **59**, 737 (1959).

identified by melting points and mixture melting points. The esters were identified by comparing their infrared spectra with those of authentic samples. It was found that the relative ratios of the products are nearly independent of the concentration of *m*-chlorobenzaldehyde. When the epoxide, phosphine and *m*-chlorobenzaldehyde, in equimolar amounts, were allowed to react for 20 hr., the ratios reported above remained essentially unchanged (with the exception of *m*-chlorobenzaldehyde).

Competition experiments in which carbomethoxymethylenetriphenylphosphorane was treated with mixtures of benzaldehyde and *m*-chlorobenzaldehyde in various mole ratios have shown, as does the rate data, that the ylid prefers the more reactive *m*-chlorobenzaldehyde. Consequently, the relatively large amount of ethyl cinnamate obtained from the reaction of the epoxide with tributylphosphine suggests that mechanism (d) rather than mechanism (c) is operative and that the rate constants for decomposition of the betaine to tributylphosphine oxide and ethyl cinnamate and to carbethoxymethylenetributylphosphorane and benzaldehyde are of the same order of magnitude. However, we cannot rule out mechanism (c), for it is possible that some or all of the ethyl cinnamate is being formed by attack of tributylphosphine at the epoxy oxygen, a reaction path which does not require the intermediacy of the betaine. Tributylphosphine is not peculiar in its reaction with epoxides because triphenylphosphine also behaves in an analogous manner in its reaction with *trans*-ethyl phenylglycidate.[8]

The data obtained from the reaction of tributylphosphine with *trans*-ethyl phenylglycidate provide conclusive proof that betaine formation in the Wittig reaction of stable ylids is reversible and mechanisms (a) and (b) are thus eliminated.

Work is continuing in these laboratories to distinguish between mechanisms (c) and (d), and the mechanism of the Wittig reaction will be the subject of a forthcoming publication.

(8) The stereochemistry and modes of reaction of 2,3-epoxy esters and amides with tributylphosphine and triphenylphosphine will be the subject of a forthcoming publication by A. J. Speziale and C. C. Tung; manuscript in preparation.

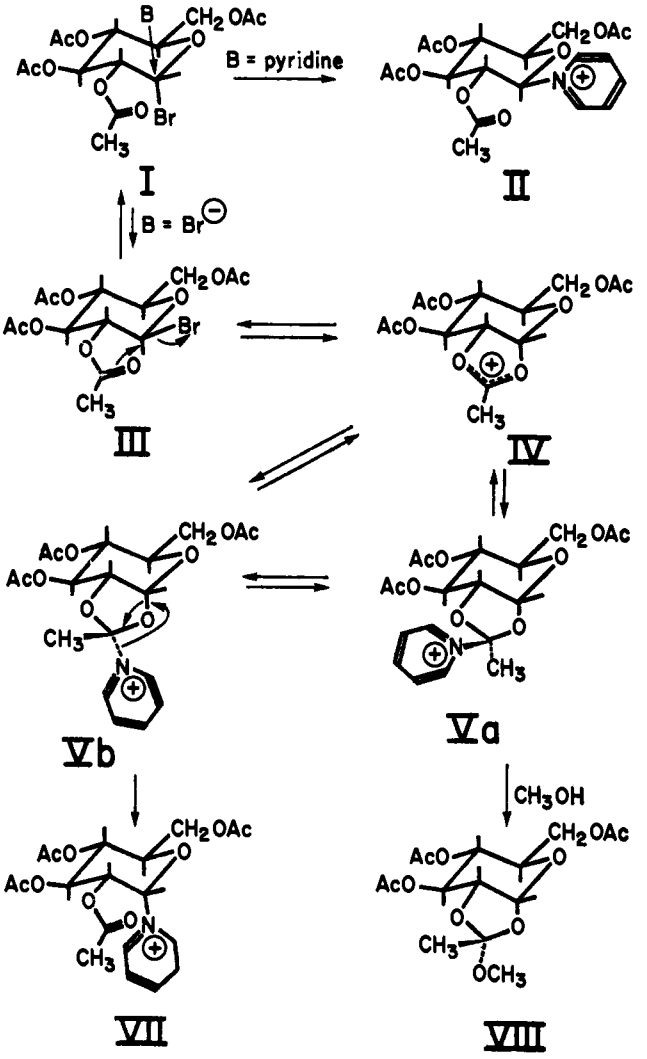
MONSANTO CHEMICAL COMPANY
AGRICULTURAL CHEMICALS DIVISION
ST. LOUIS, MISSOURI
A. J. SPEZIALE
D. E. BISSING

RECEIVED APRIL 3, 1963

The Mechanism for the Formation of 1,2-*cis*-Pyridine Nucleosides from 1,2-*cis*-Acetohalogenosugars. A Novel Rearrangement

Sir:

The reaction of tetra-*O*-acetyl-α-D-glucopyranosyl bromide (I) with dry pyridine yielded a mixture of the anomeric *N*-(2,3,4,6-tetra-*O*-acetyl-D-glucosyl)-pyridinium bromides. The anomeric hydrogens of these products in deuterium oxide produced doublets in their n.m.r. spectra at 6.89 p.p.m. (spacing, 3 c.p.s.) and 6.34 p.p.m. (spacing, 8 c.p.s.) from tetramethylsilane (external) which are characteristic[1,2] for the α-(VII) and β-(II) anomers,[3] respectively. Thus, the relative intensities of these signals provided a convenient analysis of the product. When the reaction was followed polarimetrically, the change in optical rotation corresponded closely to a first-order process when the initial concentration of I was low, 2.1% (w./v.), and virtually only the β-anomer (II) was formed. However, when the initial concentration of I was 32.7%, an induction period was noted and, therefore, it was apparent that the product of the initial reaction became involved in a faster process. The relative amounts of the β (II) and α (VII) anomeric forms found in the product was now 2:3. Thus, the induced reaction led to the formation of the α-anomer (VII).



The induction period was also present when the initial concentration of I was about 16% and the anomers were formed in equal amounts. The same course of reaction was obtained when half of the pyridine was replaced by acetonitrile although the more polar solvent gave rise to a somewhat increased rate of reaction. When the reaction of I (16% initial concentration) was carried out in pyridine containing one mole of tetra-*n*-butylammonium bromide per mole of I, the rate of reaction was much greater and the induction period was not present. Only the α-pyridinium glucoside (VII) was formed. When tetra-*n*-butylammonium perchlorate was used instead of the bromide, the induction period reappeared and the product comprised a 2:3 mixture of the β- and α-forms, respectively.

These results clearly pointed to an initial reaction wherein the α-bromide (I) underwent nucleophilic attack by pyridine with inversion of the anomeric center to produce the β-pyridinium bromide (II). The bromide ion thus liberated then participated in the faster process by making a nucleophilic attack on the starting material (I) to form the anomer of I, tetra-*O*-acetyl-β-D-glucopyranosyl bromide (III). It is conceivable that VII was formed by direct replacement of

(1) R. U. Lemieux, R. K. Kullnig, H. J. Bernstein and W. G. Schneider, *J. Am. Chem. Soc.*, **80**, 6098 (1958).
(2) R. U. Lemieux and J. W. Lown, *Can. J. Chem.*, **41**, 889 (1963).
(3) E. Fischer and K. Raske, *Chem. Ber.*, **43**, 1750 (1910).