Olefin Coordination Compounds of Rhodium. III. The Mechanism of Olefin Isomerization

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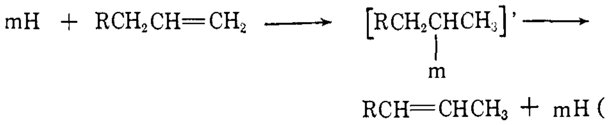
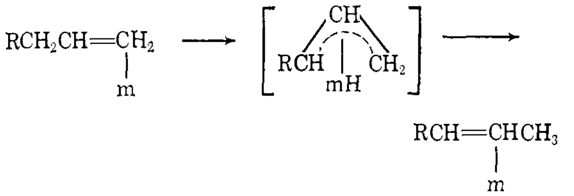
Abstract: A mechanism is proposed for the isomerization of linear butenes with a soluble rhodium catalyst. It is a modification of addition and elimination of rhodium hydride at the olefin bond and involves an intermediate (formulated as a rhodium(III) hydride with coordinated olefin) which exchanges with free olefin faster than with solvent proton. The mechanism is based principally upon deuterium transfer which accompanies isomerization of deuterated olefin or in deuterated solvent.

Migration of unsaturation in terminal olefins is catalyzed by compounds of many transition metals including titanium,[1] chromium,[2] iron,[2,3] molybdenum,[3e] cobalt,[3c,4] rhodium,[5] iridium,[5a,b,e] nickel,[2] palladium,[5a,6] and platinum.[5a,e,6c,d,7] Two isomerization mechanisms have been favored: (a) addition and elimination of a kinetically long-lived metal hydride[4d,5a,7] (eq 1) and (b) rearrangement through a transitory π-allyl hydride[1a,3f,5b,e] (eq 2). The first mechanism appears to be the better basis for describing most of the results of ref 1–7; Manuel[3e] has cited some of the supporting evidence. In addition, Davies[6a] found that isomerization of $C_5H_{11}CD_2CH{=}CH_2$ yielded little if any $C_5H_{11}CD{=}CHCH_2D$, the predicted product of the π-allyl mechanism. Further, it will be noted that the addition–elimination mechanism requires that the metal catalyst be supplied as hydride. Most of the isomerizations of ref 1–7 were accomplished with metal hydrides or in the presence of substances (protonic acid, an alcohol, or hydrogen, for example) which are known to convert transition metal compounds to hydrides.[8] Some authors[3e,5a] describe these substances as cocatalysts, and induction periods have been encountered which are consistent with hydride formation as required in eq 1 but which would not be expected for eq 2.



$$\mathrm{mH} + \mathrm{RCH_2CH{=}CH_2} \longrightarrow [\underset{\displaystyle \mathrm{m}}{\mathrm{RCH_2\overset{}{C}HCH_3}}]' \longrightarrow \mathrm{RCH{=}CHCH_3} + \mathrm{mH} \quad (1)$$



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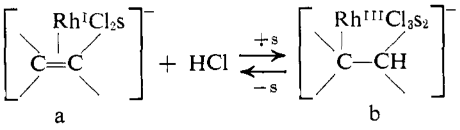
A rhodium catalyst used in the synthesis of 1-butene from ethylene[9] is an efficient olefin isomerization catalyst at temperatures as low as −25°, and examination of that isomerization provides further substantial evidence that reaction occurs through hydride addition–elimination.

Results and Discussion

Catalyst. The catalyst for olefin isomerization is obtained by a fast anaerobic reaction of $[(C_2H_4)_2RhCl]_2$[10] or 2,4-pentanedionatobis(ethylene)rhodium(I),[11] $acacRh(C_2H_4)_2$, with HCl. These inactive rhodium(I) compounds are converted into a catalytically active equilibrium mixture containing rhodium(III) which can be described by eq 3 (s is a solvent molecule, the olefin



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in a is ethylene or a linear butene, and the alkyl in b is ethyl or butyl).[9b] The oxidation state of most of the rhodium in the catalyst solution depends on the HCl concentration. As it increases, an absorption appears

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[1] (a) C. S. Marvel and J. R. Rogers, *J. Polymer Sci.*, **49**, 335 (1961); (b) G. D. Cooper and H. L. Finkbeiner, *J. Org. Chem.*, **27**, 1493 (1962); (c) F. H. C. Edgecombe, *Tetrahedron Letters*, 1161 (1962); H. Bestian and K. Clauss, *Angew. Chem. Intern. Ed. Engl.*, **2**, 704 (1963); (d) A. Shimizu, T. Otsu, and M. Imoto, *J. Polymer Sci.*, **B3**, 449 (1965); (e) D. Wanbrey, A. Barnatt, and W. Gerrard, *ibid.*, **B3**, 357 (1965).

[2] Y. Chauvin and G. Lefebvre, *Compt. Rend.*, **259**, 2105 (1964).

[3] (a) H. W. Sternberg, R. Markby, and I. Wender, *J. Am. Chem. Soc.*, **78**, 5704 (1956); (b) H. W. Sternberg, R. Markby, and I. Wender, *ibid.*, **79**, 6116 (1957); (c) F. Asinger and O. Berg, *Ber.*, **88**, 445 (1955); (d) J. Arnett and R. Petit, *J. Am. Chem. Soc.*, **83**, 2954 (1961); (e) T. A. Manuel, *J. Org. Chem.*, **27**, 3941 (1962); (f) R. Petit, G. Emerson, and J. Mahler, *J. Chem. Educ.*, **40**, 175 (1963).

[4] (a) I. J. Goldfarb and M. Orchin, "Advances in Catalysis," Vol. 9, Academic Press Inc., New York, N. Y., 1957, p 609; (b) I. Wender, *et al.*, *J. Am. Chem. Soc.*, **78**, 5401 (1956); (c) G. L. Karapinka and M. Orchin, *J. Org. Chem.*, **26**, 4187 (1961); (d) R. F. Heck and D. S. Breslow, *J. Am. Chem. Soc.*, **83**, 4023 (1961); (e) M. Johnson, *J. Chem. Soc.*, 4859 (1963).

[5] (a) J. F. Harrod and A. J. Chalk, *J. Am. Chem. Soc.*, **86**, 1776 (1964); (b) R. E. Rinehart and J. S. Lasky, *ibid.*, **86**, 2516 (1964); (c) R. D. Gillard, J. A. Osborn, P. B. Stockwell, and G. Wilkinson, *Proc. Chem. Soc.*, 284 (1964); (d) R. E. Rinehart and R. W. Fuest, *Chem. Eng. News*, **43** (7), 40 (1965); (e) J. K. Nicholson and B. L. Shaw, *Tetrahedron Letters*, 3533 (1965).

[6] (a) N. R. Davies, *Nature*, 201, 490 (1964); N. R. Davies, *Australian J. Chem.*, 17, 212 (1964); (b) G. C. Bond and M. Hellier, *J. Catalysis*, **4**, 1 (1965); (c) M. Feller, H. M. Brennan, and H. S. Seelig, U. S. Patent 2,960,550 (Nov 15, 1950); (d) M. Feller, U. S. Patent 2,960,551 (Nov 15, 1960); (e) M. B. Sparke, L. Turner, and A. J. M. Wenham, *J. Catalysis*, **4**, 323 (1965).

[7] G. C. Bond and M. Hellier, *Chem. Ind.* (London), 35 (1965); J. Milgrom and W. H. Urry, Abstracts, Proceedings of the 7th International Conference on Coordination Chemistry, Stockholm, Sweden, 1962, p 264.

[8] J. Chatt and B. L. Shaw, *Chem. Ind.* (London), 931 (1960); L. Vaska and J. W. Di Luzio, *J. Am. Chem. Soc.*, **83**, 2784 (1961); J. Chatt, B. L. Shaw, and A. E. Field, *J. Chem. Soc.*, 3466 (1964).

[9] (a) T. Alderson, E. L. Jenner, and R. V. Lindsey, Jr., *J. Am. Chem. Soc.*, **87**, 5638 (1965); (b) R. Cramer, *ibid.*, **87**, 4717 (1965).

[10] R. Cramer, *Inorg. Chem.*, **1**, 722 (1962).

[11] R. Cramer, *J. Am. Chem. Soc.*, **86**, 217 (1964).

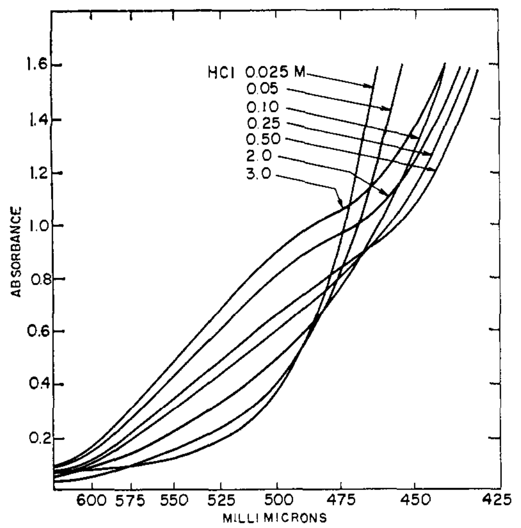

Figure 1. $[(C_2H_4)_2RhCl]_2$ in ethanolic HCl.

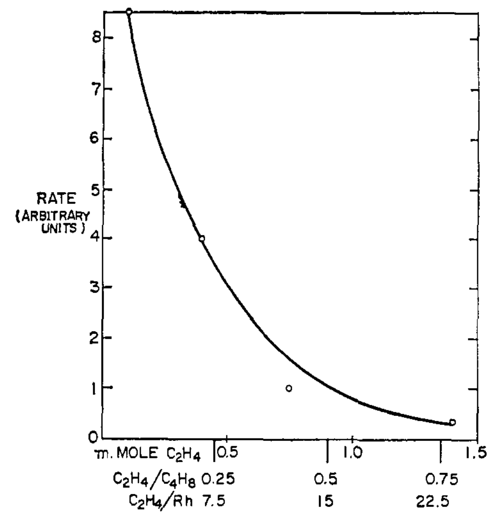

Figure 2. Effect of C_2H_4 on the isomerization of 1-butene.

at about 485 mμ (Figure 1) which is consistent with the formation of a six-coordinate chloridorhodium(III) compound[12] such as b. Nmr spectra of catalyst solutions in 3 M methanolic HCl suggest that 35% of the hydrocarbon is present as olefin and 65% as an alkyl group.

Isomerization of 1-Butene. In this work attention was focused on linear butenes. These were isomerized in methanol solutions which were typically 0.01 M in Rh and 0.1 M in HCl at temperatures between -25 and 0°. There was no induction period and, with exclusion of air, the catalyst solutions usually remained active indefinitely.

The rate of isomerization was followed by vpc analysis. The data correspond to a first-order, reversible reaction[13] (eq 4) which indicates that the rate is proportional to the concentration of 1-butene. At

$$\text{1-butene} \rightleftarrows \text{2-butenes} \qquad (4)$$

limiting concentrations the rate also depends upon the concentration of Cl^-, H^+, and Rh. Isomerization does not occur in the absence of halide (Cl^-, Br^-, or I^-). These results all resemble the behavior of the catalyst in the dimerization of ethylene.[9b] In methanol which is 0.2 M in HCl and 0.012 M in Rh, the rate is 1.9×10^{-2} min^{-1} (ml of catalyst solution)$^{-1}$ at 0°. Isomerization of 1-butene is inhibited by olefins which are preferentially coordinated by rhodium. The effect of ethylene at $-10°$ is shown in Figure 2. At higher temperatures ethylene would be consumed by dimerization to butene but at $-10°$ dimerization is so slow that ethylene is a persistent inhibitor. Tracer experiments indicate that below $-10°$ ethylene undergoes reactions analogous to those leading to isomerization of 1-butene but there can, of course, be no double-bond migration in ethylene.[14] Inconstant traces of ethylene (introduced as part of the catalyst molecule and remaining undimerized when the catalyst is activated with HCl) may be responsible for some scatter in the measured rate of 1-butene isomerization. Ethylene is always detected when isomerization products are examined by vpc.

Other olefins retard rhodium-catalyzed isomerization of 1-butene to varying degrees, approximately in the order acrylonitrile > butadiene >> acetylene > vinyl chloride ≈ ethylene > tetrafluoroethylene. Also, compounds which coordinate strongly with rhodium will interfere with or stop isomerization of 1-butene. Thus, addition of 1 mmole of acetonitrile to a reaction solution containing 6 mmoles of 1-butene and 0.01 mmole of rhodium slowed isomerization to less than 0.01 of the uninhibited rate.

Isomerization of 2-Butenes. Both *cis*-2-butene and *trans*-2-butene isomerize rapidly at 0° in the presence of the rhodium catalyst to equilibrium mixtures of linear butenes. Like the isomerization of 1-butene, the kinetic data fit first-order reversible reactions for the first 80% of reaction. The usual plots for such reactions give as the slope the sum of the forward and reverse rate constants[13] and these are shown in Table I.

Table I. Rates for the Reaction Butene $\underset{k'}{\overset{k}{\rightleftarrows}}$ Butene Isomers

Butene	$k + k' \times 10^2$ min^{-1}
1-Butene	1.9
cis-2-Butene	2.7
trans-2-Butene	0.8

The rate constants of Table I are of limited value, however, because of uncertainty concerning the *effective* catalyst concentration. The three butenes compete for the catalyst and the catalyst concentration is virtually greatest for the butene isomer which coordinates most strongly. The situation is analogous to competing acid-catalyzed reactions in the presence of a

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(12) C. K. Jørgensen, *Acta Chem. Scand.*, 10, 500 (1956).

(13) A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," 2nd ed, John Wiley and Sons, Inc., New York, N. Y., 1961, p 186.

(14) Preferential coordination of ethylene by rhodium has an important effect on the composition of the butenes obtained when ethylene is dimerized. Isomerization of 1-butene, the initial dimerization product, is inherently far faster than ethylene dimerization. Accordingly, it might be expected that the distribution of isomers in the product would be established by thermodynamics. However, mixtures containing 38% 1-butene (six times the equilibrium concentration) may be prepared under high ethylene pressures where coordination of 1-butene and its subsequent isomerization are inhibited.

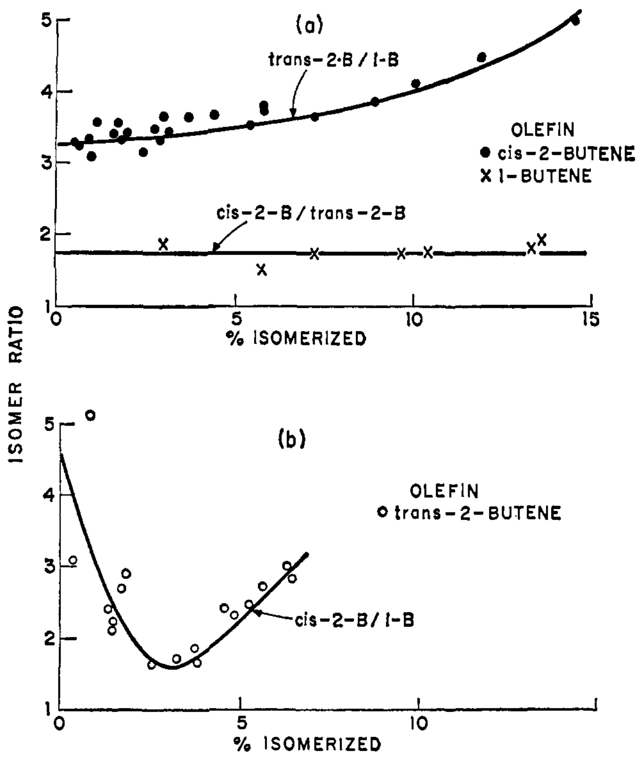
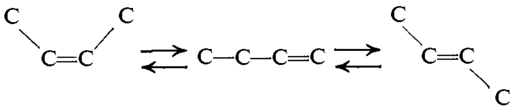


Figure 3. Product ratios from the isomerization of linear butenes.

limited quantity of acid—the strongest base captures most of the catalyst. Consequently the effective catalyst concentration for each isomer changes with the composition of the mixture during the reaction.

Although it has been suggested that inner olefins are interconverted through a terminal olefin[5d,6b] (eq 5),



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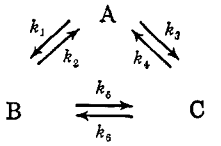
the results reported here, are consistent with the scheme of eq 6. Relative values for the individual rate constants



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A = 1-butene, B = *trans*-2-butene, C = *cis*-2-butene

of eq 6 are accessible by a procedure described by Haag and Pines.[15]

Isomerization of any of the linear butenes with rhodium catalyst initially gives the other two butenes in a kinetically determined ratio different from the equilibrium ratio. If, then, one starts with 1-butene, the initial ratio of *trans*-2-butene/*cis*-2-butene can be expected to give the value for the ratio k_1/k_3 (eq 6). By determining the ratio B/C at low total conversion and extrapolating to zero time, k_1/k_3 can be evaluated. Similarly, values can be found for k_2/k_5 and k_4/k_6 starting with *trans*-2-butene and *cis*-2-butene. Since at equilibrium the forward and reverse rates must be equal, a set of rate constant ratios can also be calculated from the equilibrium concentrations of the linear butenes, *viz.* 3.00% 1-butene, 21.8% *cis*-2-butene, and 75.2% *trans*-2-butene (at 0°).[16] These give values of k_1/k_2 = 25.1, k_3/k_4 = 7.25, and k_5/k_6 = 1/3.45.

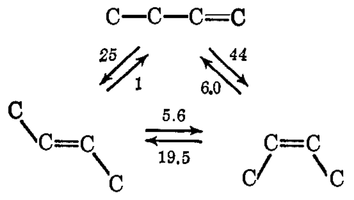

Figure 4. Relative rate constants for the isomerization of linear butenes with HCl and acacRh$(C_2H_4)_2$ at 0.

Experimentally, estimation of limiting isomer ratios appears to be more precise when 1-butene or *cis*-2-butene is isomerized. The results (Figure 3a) give the values k_3/k_1 = 1.75 and k_4/k_6 = 1/3.25. When these are combined with the thermodynamic ratios, the results of Figure 4 are obtained. The calculated value for k_5/k_2 is 5.6 which corresponds reasonably to the experimental ratio (Figure 3b) of *ca.* 4. This internal consistency supports the isomerization scheme of eq 6. (More compelling evidence involving isomerization of *cis*-2-butene and *trans*-2-butene in CH_3OD is described later.) These relative rate constants (at 0°) are all within a factor of 3 of those found by Haag and Pines[15] for isomerization of 1-butene with a heterogeneous sodium–alumina catalyst (at 30°).

Deuteration. When 1-butene is isomerized in CH_3OD, deuterated butenes are produced. Isomerization and H–D exchange appear to be different aspects of the same reaction (and not separate, concurrent reactions) since they respond equivalently to changes in reaction conditions.

(a) When ethylene is added to the reaction mixture, both isomerization and deuteration of 1-butene are inhibited. (Ethylene is deuterated instead of butene.)

(b) At −33° in methanol, isomerization virtually stops; simultaneously, butene is not deuterated.

(c) In a less basic medium than methanol (*viz.*, chloroform), 1-butene may be isomerized at −35°, and under these conditions H–D exchange also occurs.

(d) H–D exchange and isomerization have about the same rate and, to a first approximation, one deuterium is introduced for each molecule of 1-butene that is isomerized. Data supporting this conclusion are summarized in the last two columns of Table II in which the quantity of 1-butene isomerized (calculated from vpc analysis) is compared with the amount of deuteration (mass spectrometric analysis). It will be noted that generally the extent of H–D exchange approaches but is somewhat smaller than the amount of isomerization. (A rationalization of this discrepancy will be discussed later.)

If the three butenes in the isomerized–deuterated product are separated and each is analyzed for its deuterium content, it is found that *part of the 1-butene is deuterated while much of the 2-butene contains no deuterium.* Results typical of about 25 experiments are summarized in Table III. The presence of substantial amounts of deuterated 1-butene and nondeuterated 2-butenes in the isomerization–deuteration

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[15] W. O. Haag and H. Pines, *J. Am. Chem. Soc.*, **82**, 387 (1960).

[16] J. R. Kilpatric, E. J. Prosen, K. S. Pitzer, and F. D. Rossin, *J. Res. Natl. Bur. Std.*, **36**, 559 (1946).

Table II. Isomerization and Deuteration of 1-Butene

Expt	Temp, °C	Time, hr	[HCl], *M*	1-Butene in product, %	1-Butene isomerized, mmoles	Deuterium introduced,[b] mmoles
1	−30	12	0.5	93.4	0.17	0.18
2	−23	1	0.5	92.2	0.20	0.25
3	−25	2	0.5	77.5	1.38	0.90
4	−25	4.5	0.5	64.6	2.69	2.06
5	−25	4	0.5	59.9	3.02	2.27
6	0	0.3	0.1	51.3	3.90	3.40
7	−23	6.7	0.5	40.7	3.55 (3.7)[a]	3.17
8	0	0.25	0.5	22.6	6.16 (6.4)[a]	6.01
9	0	0.1	2.0	20.8	6.34 (7.4)[a]	4.49
10	−25	456	0.5	5.1	7.58 (8.4)[a]	7.59

[a] Parenthetical value is a minimal estimate of the sum of 1-butene isomerized and of *cis*-2-butene converted to *trans*-2-butene. [b] Measured by low-voltage mass spectroscopy except for expt 2, 6, 8, and 10 for which fragmentation patterns were used.

Table III. Composition of Butenes from Isomerization–Deuteration of 1-Butene

Expt	Temp, °C	Time, hr	[HCl], *M*	Butene (%)	%				Fraction of deuterium[a]
					C_4H_8	C_4H_7D	$C_4H_6D_2$	$C_4H_5D_3$	
1	−25	1	0.5	1-Butene (91.4)	89	10	<1		0.83
				cis-2-Butene (5.0)	74	25	<1		0.10
				trans-2-Butene (3.6)	76	23	<1		0.07
2	−25	4.5	0.5	1-Butene (64.6)	79	19	2		0.56
				cis-2-Butene (20.0)	73.5	23	3	0.5	0.22
				trans-2-Butene (15.4)	66	29	4.5	0.5	0.22
3	−23	6.7	0.5	1-Butene (40.7)	60	33	7		0.38
				cis-2-Butene (27.5)	61	32	7		0.25
				trans-2-Butene (31.8)	52	38	10		0.37
4	0	0.3	0.1	1-Butene (51.3)	72	24	3	1	0.39
				cis-2-Butene (28.4)	60	32	7	1	0.32
				trans-2-Butene (20.3)	53	35	10	2	0.29
5	0	0.25	0.5	1-Butene (22.6)	50	34	12	3	0.23
				cis-2-Butene (35.1)	41	36	15	5	0.40
				trans-2-Butene (40.8)	52	33	11	3	0.37
6	0	0.1	2.0	1-Butene (20.8)	65	27	6	2	0.17
				cis-2-Butene (26.3)	63	26	7	4	0.26
				trans-2-Butene (52.9)	57	31	9	3	0.57

[a] (Deuterium in specified olefin)/(deuterium in entire product).

product in addition to approximately one-to-one correspondence of isomerization and deuteration places severe restrictions on proposed reaction mechanisms. Additional limitations are imposed by the position of substitution in the deuterated butenes.

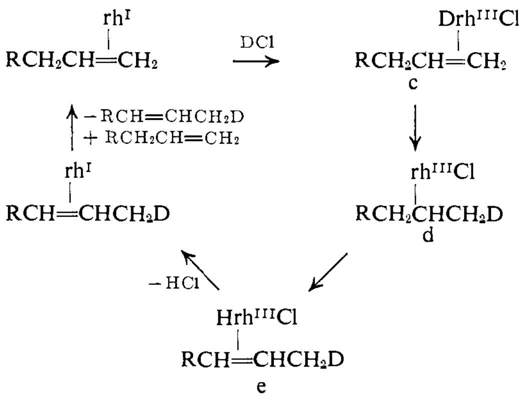
Infrared and nmr spectroscopy show that the deuterium in 1-butene is located, at least principally, on C_2. A sample of 1-butene containing 28.5% C_4H_7D and 4.5% $C_4H_6D_2$, isolated from an isomerization mixture by vpc, had an infrared absorption at 2252 cm^{-1} which is attributed to the stretching of a bond connecting D and olefinic C. There was no detectable infrared absorption corresponding to a C–D bond of saturated carbon. The pmr absorption of 1-butene is not obscured by 2-butene so the spectrum of an unfractionated isomerization–deuteration product could be studied. The ratio of integrated absorptions for 1-butene in a product containing 30% C_4H_7D was C_1:C_2:C_3:C_4 = 2:0.88:2.03:3.00, indicating accumulation of D on C_2. This assignment is substantiated by the appearance of new inflections in that part of the nmr spectrum attributed to protons on C_1.

Although both the saturated and unsaturated carbons of 2-butenes are deuterated, the preferred displacement is again at C_2. Thus, the mixture of 2-butenes from 17% isomerization (with corresponding deuteration) of 1-butene had infrared absorptions at both 2230 (D–C unsaturated) and 2180 cm^{-1} (D–C saturated), but the ratio of the absorptivities was about 6:1 (2230:2180 cm^{-1}). As reaction proceeds, the proportion of deuterium on saturated carbon increases. Thus, *cis*-2-butene, isolated after 1-butene was 95% isomerized, had infrared absorptions at 2252 and 2183 cm^{-1} (absorptivity ratio about 2:1). Corresponding absorptions at 2232 and 2188 cm^{-1} (absorptivity ratio approaching 1:1) were found in the infrared spectrum of *trans*-2-butene from the same isomerization product.

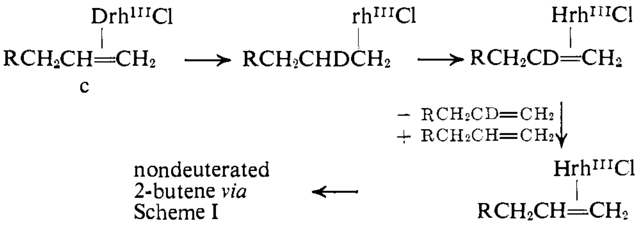
Mechanism. The results of the H–D exchange experiments cannot be explained by either the π-allyl or the unmodified metal hydride addition–elimination mechanism. If the proposed π-allyl hydride is transitory, transfer of hydrogen would be intramolecular and no exchange with solvent would be expected. If, on the other hand, the π-allyl hydride persists long enough to exchange hydride with solvent deuterium, then, when the π-methallyl group was released as 1-butene, deuterium would be introduced at C_3 but not at C_2. A second relationship which is not accounted for by the π-allyl mechanism is the formation of deuterated 1-butene and nondeuterated 2-butenes in nearly equal amounts. A third objection was encountered in connection with the isomerization–deuteration of *cis*- and *trans*-2-butenes and will be discussed later.

The simple hydride addition and elimination mechanism (eq 2) indicates an intermolecular transfer of hydrogen from an isomerized molecule to substrate olefin. Deuteration requires an additional step in which hydride on the metal is exchanged with solvent deuterium. But the near equivalence of isomerization and deuteration under a variety of reaction conditions suggests a controlled H-D exchange by which approximately one deuterium is introduced in each isomerization cycle. This would be accomplished if (a) *rhodium(I) were oxidized by DCl to a rhodium(III) deuteride (which is the catalytic species) and (b) rhodium(III) hydride were reduced to rhodium(I) and HCl when the isomerized olefin is released (Scheme I).*[17] The only deuterated olefin that would result from the sequence of Scheme I is $CH_3CH{=}CHCH_2D$, a minor component of the isomerization product. In order to account for the principal deuterated olefins, we propose that the intermediate hydride (c, Scheme I) can exchange olefin according to the series of reactions given in Scheme II.

Scheme I. Deuterium Exchange during Isomerization



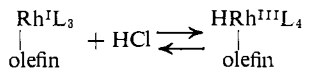
Scheme II. Formation of Deuterated Terminal Olefin



This proposal is supported by the observation that ethylene exchange in an analog of c, $C_2H_5Rh^{III}L_4(CH_2{=}CH_2)$, appears to be faster[9b] than isomerization of 1-butene.[18] Results reported by Sacco and Ugo[19] indicate that a rhodium(III) hydride may be stable in solutions containing HCl.

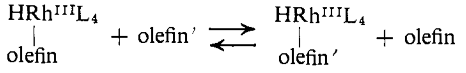
Isomerization, then, proceeds by four reactions (eq 7-10) which are inherently reversible but which may be virtually unidirectional in a specific isomerization system:

(a) oxidation of rhodium(I) to rhodium(III) by HCl



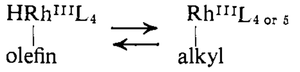
$$\underset{\text{olefin}}{\overset{\text{Rh}^{\text{I}}\text{L}_3}{|}} + \text{HCl} \rightleftarrows \underset{\text{olefin}}{\overset{\text{HRh}^{\text{III}}\text{L}_4}{|}} \tag{7}$$

(b) olefin exchange of rhodium(III) complexes



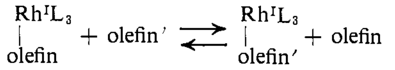
$$\underset{\text{olefin}}{\overset{\text{HRh}^{\text{III}}\text{L}_4}{|}} + \text{olefin}' \rightleftarrows \underset{\text{olefin}'}{\overset{\text{HRh}^{\text{III}}\text{L}_4}{|}} + \text{olefin} \tag{8}$$

(c) hydride addition in a rhodium(III) olefin complex to give a rhodium(III) alkyl



$$\underset{\text{olefin}}{\overset{\text{HRh}^{\text{III}}\text{L}_4}{|}} \rightleftarrows \underset{\text{alkyl}}{\overset{\text{Rh}^{\text{III}}\text{L}_{4\text{ or }5}}{|}} \tag{9}$$

(d) olefin exchange in rhodium(I) complexes



$$\underset{\text{olefin}}{\overset{\text{Rh}^{\text{I}}\text{L}_3}{|}} + \text{olefin}' \rightleftarrows \underset{\text{olefin}'}{\overset{\text{Rh}^{\text{I}}\text{L}_3}{|}} + \text{olefin} \tag{10}$$

Application of these reactions to the isomerization–deuteration of 1-butene is illustrated in Scheme III. The products are shown in italics, and only the principal products and reactions are considered. Further reaction of these products leads to further rearrangement and more extensive deuteration. When alternative reactions (both significant) are encountered, the less important is indicated by a dotted arrow.

Deuteration of $rh^I(CH_2{=}CHC_2H_5)$ leads principally (eq 1, 2, and 3, Scheme III) *via* $rh^{III}CH_2CHDC_2H_5$ to $Hrh^{III}(CH_2{=}CDC_2H_5)$. Although experiments with $CH_3CD_2CH{=}CH_2$, to be described later, suggest an isotope effect favoring retention of deuterium in the olefin, this is not essential. Competitive loss of deuterium from $rh^{III}CH_2CHDC_2H_5$ would be a trivial step which would merely reverse eq 2. The only forward-going reaction of $rh^{III}CH_2CHDC_2H_5$ is given by eq 3. Deuterated 1-butene, one of the unexpected reaction products, is largely displaced from the product by substrate 1-butene (present in high concentration). The nondeuterated complex, $Hrh^{III}(CH_2{=}CHC_2H_5)$, continues to undergo hydride addition and elimination at the olefin bond. Usually hydrogen adds to C_2 but this is a trivial step since elimination regenerates $Hrh^{III}(CH_2{=}CHC_2H_5)$. Occasionally addition of hydride to C_1 will occur (eq 5, Scheme III). If elimination reestablishes a double bond between C_1 and C_2, the reaction is trivial, but if the new olefin bond is between C_2 and C_3, a rhodium(III) hydride of an internal olefin is formed (eq 6). This hydride may lose a proton (eq 7) to give $rh^I(CH_3CH{=}CHCH_3)$ from which the other unexpected product, nondeuterated 2-butene, is displaced by 1-butene (eq 8).

The reaction path (cycle A) which has just been outlined provides (1) a route to deuterated 1-butene, (2) a route to nondeuterated 2-butene, and (3) a one-to-one relation between deuteration and isomerization. The last mentioned relation follows if $Hrh^{III}(CH_2{=}CDC_2H_5)$ undergoes olefin exchange and hydride addition to coordinated olefin faster than reduction to $rh^I(CH_2{=}CDC_2H_5)$, while, on the other hand, $Hrh^{III}(CH_3CH{=}CHCH_3)$ is reduced to $rh^I(CH_3CH{=}CHCH_3)$ rather than undergoing olefin exchange with 1-butene. If this relative order of reactivity is maintained over the studied temperature range, then the one-to-one deuteration–isomerization ratio would be maintained (as is observed) even though the over-all rate changed considerably. The difference in the reaction paths taken by $Hrh^{III}(CH_2{=}CHCH_2CH_3)$ and $Hrh^{III}(CH_3CH{=}CHCH_3)$ may be a consequence of slower olefin displacement or lower stability of rhodium(III) in the latter compound.

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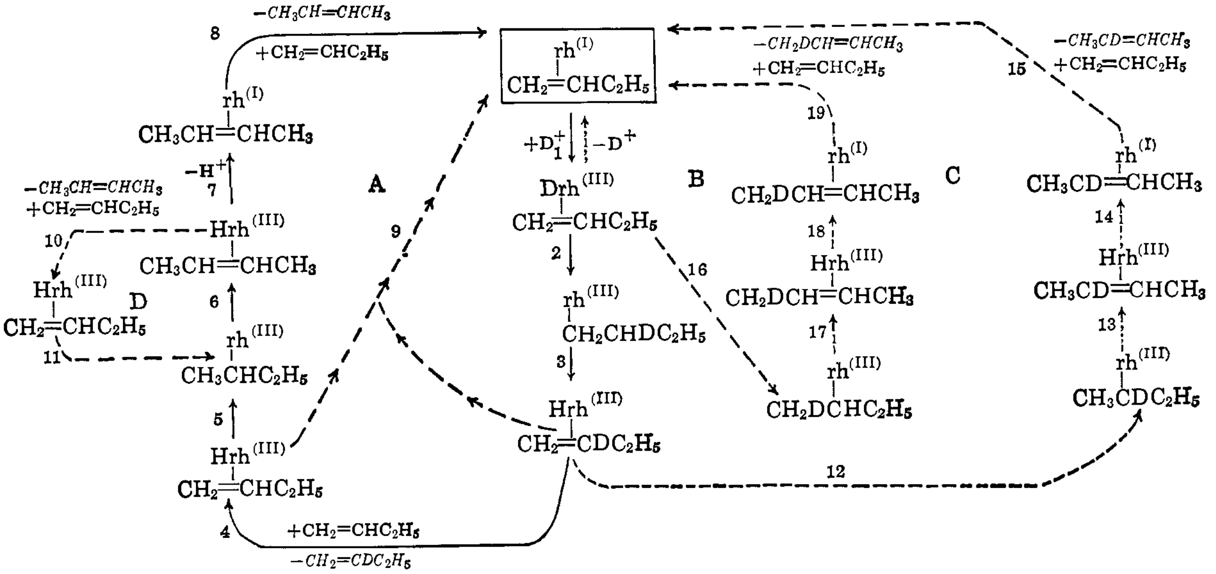
[17] This reaction sequence is analogous to the mechanism proposed for ethylene dimerization by the rhodium catalyst.[9b]

[18] Exchange of ethylene in four-coordinate complexes of rhodium(I) is much faster than isomerization: R. Cramer, *J. Am. Chem. Soc.*, **86**, 217 (1964).

[19] A. Sacco and R. Ugo, *J. Chem. Soc.*, 3274 (1964).

Scheme III. Isomerization–Deuteration of 1-Butene (Products Are in Italics; Minor Reactions Are Shown by Dotted Arrows)



Certain of the alternative reactions outlined in Scheme III are significant and may now be considered. Two deuterated 2-butenes are found. The principal one, $CH_3CD{=}CHCH_3$, results when $Hrh^{III}(CH_2{=}CDC_2H_5)$ (formed in eq 3) undergoes hydride addition to C_1 (eq 12) and elimination establishes a double bond between C_2 and C_3 (eq 13). The resulting hydride, with coordinated 2-butene, $Hrh^{III}(CH_3CD{=}CHCH_3)$, yields $CH_3CD{=}CHCH_3$ *via* eq 14 and 15. Since the relative amounts of $CH_3CH{=}CHCH_3$ and d_1-2-butene are in the approximate ratio 3:1 (expt 1 and 2, Table II) and infrared shows that most of the d_1-2-butene is $CH_3CD{=}CHCH_3$, reaction 4 must occur about three times as often as reaction 13.

Table IV. Isomerization–Deuteration of *cis*-2-Butene

	Expt 1 (−25°/48 hr)			Expt 2 (0°/0.5 hr)		
	cis-2-Butene	*trans*-2-Butene	1-Butene	*cis*-2-Butene	*trans*-2-Butene	1-Butene
Composition, %	71.4	25.4	3.2	63.8	32.4	3.8
C_4H_8	96	55	39	93	44	26
C_4H_7D	2.4	39	30	3.8	42	37
$C_4H_6D_2$	1.3	4.0	19	2.3	7.7	23
$C_4H_5D_3$	0.4	1.9	8.3	0.8	3.8	9.7
$C_4H_4D_4$	0.1	0.6	2.3	0.3	1.5	3.0
$C_4H_3D_5$		0.2	0.5	0.2	0.5	1.0
cis-2-Butene isomerized		2.29 mmoles		2.90 mmoles		
D introduced		1.78 mmoles		3.07 mmoles		

The other deuterated 2-butene, $CH_2DCH{=}CHCH_3$, is formed when $Drh^{III}(CH_2{=}CHC_2H_5)$ reacts according to eq 16 and 17 instead of eq 2 (reaction cycle B of Scheme III). Since (a) the initial rate of formation of 2-deuterio-2-butene is at least five times as fast as the formation of 1-deuterio-2-butene (infrared results reported earlier) and (b) the amount of d_1-1-butene is three times the amount of d_1-2-butene, it follows that addition of D to C_2 is at least 15 times as fast as addition to C_1.

If the hydride $Hrh^{III}(CH_2{=}CHC_2H_5)$ reverted to $rh^{I}(CH_2{=}CHC_2H_5)$, then deuteration of 1-butene might be accomplished with little isomerization by shortcutting cycle A through eq 9. This reaction sequence might become important in other catalyst systems.

Finally, the increment of isomerization over deuteration that is indicated in Table II can be accounted for by one of the reaction cycles outlined in Scheme III. If coordinated 2-butene in $Hrh^{III}(CH_3CH{=}CHCH_3)$ (formed by eq 6) is occasionally displaced by 1-butene, isomerization may occur without deuteration. This would become important to the extent that cycle D (Scheme III) is repeated.

Isomerization of *cis*-2-Butene. The scheme devised to account for the products of isomerization–deuteration of 1-butene can be tested for its ability to explain the results obtained in the isomerization–deuteration of *cis*-2-butene. These are given in some detail in Table IV and may be summarized as follows.

(a) The amount of isomerization approximated (within 25%) the amount of deuteration both at −25°/48 hr and 0°/0.5 hr. The ratio of butene isomers in the products at the two temperatures was roughly the same.

(b) Unlike isomerization of 1-butene, where most of the deuterium appeared initially in unisomerized 1-butene, little deuterium is incorporated in unisomerized *cis*-2-butene. However, there is nearly as much d_2-*cis*-2-butene as d_1-*cis*-2-butene.

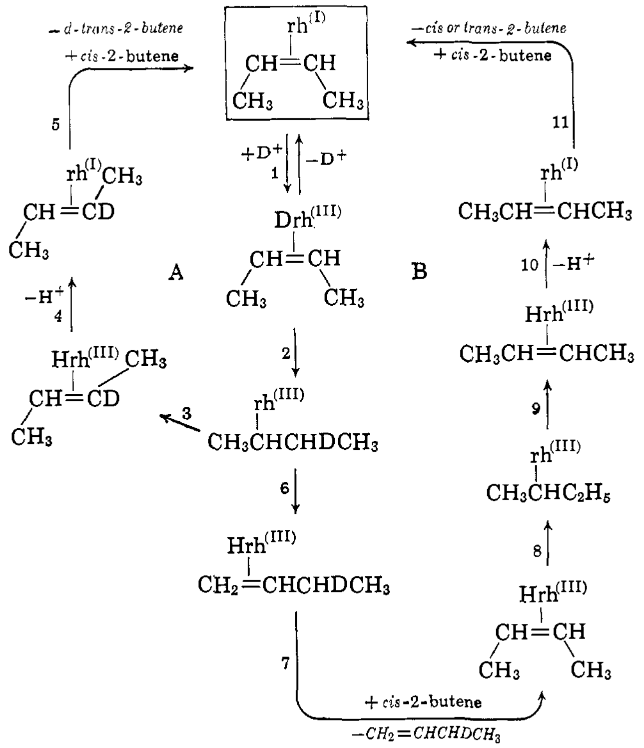
(c) To a first approximation nondeuterated and deuterated *trans*-2-butene are formed in equal amounts.

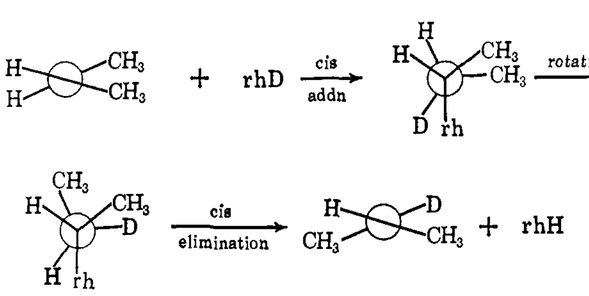
The proportion of d_1-*trans*-2-butene to more highly deuterated *trans*-2-butenes is somewhat greater than occurs in the isomerization of 1-butene (Table III).

(d) 1-Butene is near its equilibrium concentration and is highly deuterated.

These results are all consistent with the mechanism used to account for the behavior of 1-butene and this may be seen by reference to Scheme IV. The complex rh^{I}(*cis*-$CH_3CH{=}CHCH_3$) is oxidized by D^+ (eq 1) and deuteration (eq 2) can give only $rh^{III}CH(CH_3)CHDCH_3$. Hydride elimination might occur from either C_3 or C_1, the former leading to d_1-*trans*-2-butene *via* eq 3, 4, and 5 (reaction cycle A, Scheme IV). If rhodium deuteride addition is stereospecific and if elimination occurs by the microscopic reverse, isomerization should yield *d*-*trans*-2-butene but not a *d*-*cis*-2-butene (eq 11). Since there is little *d*-*cis*-2-butene (and its formation in small amount by an alternative route is expected), *this experiment provides important evidence that rhodium-catalyzed isomerization occurs by addition and elimination of hydride.*

Scheme IV. Isomerization–Deuteration of *cis*-2-Butene





(11)

A similar result would not be expected for a π-allyl intermediate. Reaction of coordinated *cis*-2-butene by stereospecific hydrogen elimination to give an allylic anion of fixed configuration followed by stereospecific readdition of deuterium is predicted to give *d*-*cis*-2-butene.[6b] Nonstereospecific reactions should yield a mixture of *cis*- and *trans*-*d*-2-butene. Finally, if the *syn* and *anti* configurations of the π-allyl complex are interconvertible and one is more stable than the other,[20] similar products might be expected from the isomerization–deuteration of both *cis*- and *trans*-2-butene. When *trans*-2-butene was isomerized in CH_3OD to the extent of 8% (2.5% 1-butene and 5.5% *cis*-2-butene), the recovered *trans*-2-butene contained 94.0% C_4H_8, 2.8% C_4H_7D, 2.0% $C_4H_6D_2$, and 0.8% $C_4H_5D_3$, while the *cis*-2-butene contained 47.1% C_4H_8, 37.9% C_4H_7D, 9.2% $C_4H_6D_2$, 4.0% $C_4H_5D_3$, and 1.3% $C_4H_4D_4$. This is essentially the mirror image of isomerization of *cis*-2-butene as would be expected for isomerization through a hydride addition and elimination mechanism.

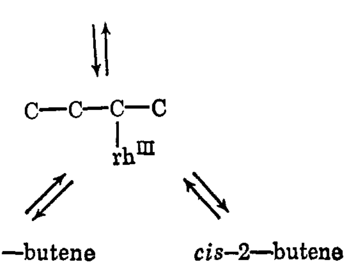
Returning to the isomerization–deuteration of *cis*-2-butene, hydride elimination from C_1 of $rh^{III}CH(CH_3)CHDCH_3$ (eq 6, Scheme IV) would yield $Hrh^{III}(CH_2{=}CHCHDCH_3)$. Although exchange generally favors coordination of 1-butene, the concentration of *cis*-2-butene is so high that it may displace 1-butene (eq 7). Accordingly, $CH_2{=}CHCHDCH_3$ will be released and some *cis*-2-butene will be isomerized to nondeuterated *trans*-2-butene by eq 8 to 11 (cycle B, Scheme IV).

Cycles A and B are regarded as the principal routes to d_1-*trans*-2-butene and nondeuterated *trans*-2-butene, respectively. Therefore, the nearly equal amount of these *trans*-2-butenes (Table IV) shows that hydride elimination at C_1 and C_3 may be competitive although the comparative rates of reactions 4 and 7 must be considered as well as the concentrations of the intermediates Hrh^{III}(*trans*-$CH_3CH{=}CDCH_3$) and $Hrh^{III}(CH_2{=}CHCHDCH_3)$.

The complex $Hrh^{III}(CH_2{=}CHCHDCH_3)$ formed by eq 6 (Scheme IV) and the $CH_2{=}CHCHDCH_3$ released in eq 7 provide a route to the other isomerization–deuteration products from *cis*-2-butene. Readdition of hydride in $Hrh^{III}(CH_2{=}CHCHDCH_3)$ (without intervening olefin displacement), reverse of 6 (Scheme IV), would probably give $rh^{III}CH(CH_3)CHDCH_3$ that is sterically equivalent to the original complex and is, therefore, a trivial reaction. However, if $CH_2{=}CHCHDCH_3$ leaves and then returns to Hrh^{III}, it provides (by cycle A, Scheme III) a route to a *cis*- and *trans*-d_1-*cis*-2-butene.

It might be expected from the relative rates given in Figure 4 that 1-butene would isomerize faster than *cis*-2-butene. In fact, isomerization of *cis*-2-butene is faster (Table I). This is consistent with the hydride addition–elimination mechanism. Isomerization of lin-

Scheme V. Catalyst Competition in Butene Isomerization



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[20] S. Bank, A. Schriesheim, and C. A. Rowe, Jr., *J. Am. Chem. Soc.*, 87, 3244 (1965).

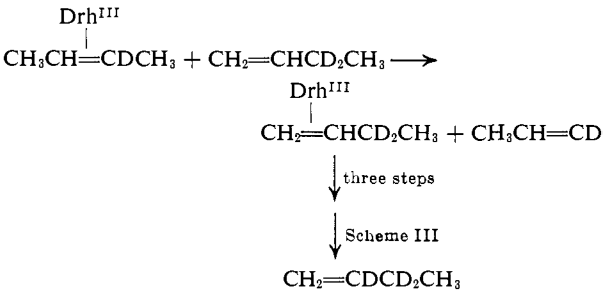
ear butenes involves a common intermediate (Scheme V). Although *cis*- and *trans*-2-butene may give this intermediate more slowly than 1-butene, they can give no other hydride addition product. 1-Butene, however, can form an *n*-butylrhodium complex (which cannot yield isomer) and the results of deuterium tagging experiments indicate it is formed 15 times as frequently as the secondary butyl complex which leads to isomerization. This "trivial" hydride addition reduces the rate of 1-butene isomerization.

Isomerization of $CH_3CD_2CH{=}CH_2$. The deuterioolefin was prepared from amyl acetate by a series of reactions analogous to those employed by Davies[6a] for synthesis of $C_5H_{11}CD_2CH{=}CH_2$. The product, like Davies', contained only about 66% of the required deuterium. The nmr spectrum indicates that only C_3 was deuterated but the mass spectrum (calculation based on parent peaks) shows about 4% $C_4H_5D_3$ (Table V) so other carbon(s) was (were) deuterated. The vpc analysis indicated the presence of 0.3% propene but no other impurity. The composition of the products following about 20% isomerization in CH_3OH solution is given in Table V and the results confirm and provide further information on the proposed mechanism for olefin isomerization.

Table V. Isomerization of $CH_3CD_2CH{=}CH_2$

	Reactant 1-Butene	Products, % 1-Butene	*trans*-2-Butene	*cis*-2-Butene
Composition, %		81.2	7.3	11.5
C_4H_8	18	12	20	20
C_4H_7D	27	22	55	63
$C_4H_6D_2$	51	56	20	15
$C_4H_5D_3$	4.0	8.4	4.4	2.7
$C_4H_4D_4$	0.6	1.2	0.5	0.4
$C_4H_3D_5$	0.1	0.2	0.2	

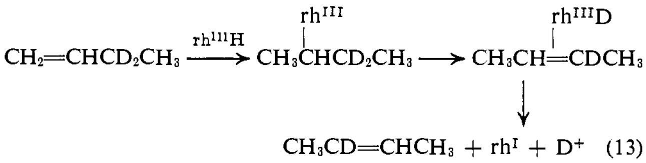
(a) It is apparent that isomerization is not simply an intramolecular transfer of hydrogen. Thus the principal 1-butene component was $C_4H_6D_2$ but the principal 2-butene species in the isomerized product was C_4H_7D corresponding to loss of deuterium. However, deuterium was not merely lost to the solvent. The 1-butene in the product contained 8.4% $C_4H_5D_3$ as compared with 4.0% in the starting material, presumably by eq 12. The extent to which it occurs reflects the minor importance of cycle D, Scheme III. Since



$$\overset{\mathrm{Drh^{III}}}{\mathrm{CH_3CH{=}CDCH_3}} + \mathrm{CH_2{=}CHCD_2CH_3} \longrightarrow \overset{\mathrm{Drh^{III}}}{\mathrm{CH_2{=}CHCD_2CH_3}} + \mathrm{CH_3CH{=}CDCH_3} \xrightarrow{\text{three steps}} \xrightarrow{\text{Scheme III}} \mathrm{CH_2{=}CDCD_2CH_3} \qquad (12)$$

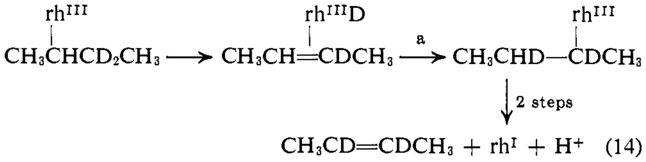
the product contained 81.2% of 1-butene of which 8.4% was $C_4H_5D_3$, 18.5 mole % isomerization produced only about 3 mole % (=0.812 × 8.4 − 4) d_3-1-butene. This corresponds reasonably with the conclusions reached from the isomerization of $CH_2{=}CHC_2H_5$ in CH_3OD.

(b) Although the proportion of $C_4H_6D_2$ in *cis*-2-butene and *trans*-2-butene is decidedly lower than in 1-butene, it might be expected that very little would be found (eq 13). Since 15 to 20% of 2-butene is $C_4H_6D_2$,



$$\mathrm{CH_2{=}CHCD_2CH_3} \xrightarrow{\mathrm{rh^{III}H}} \mathrm{CH_3\overset{rh^{III}}{C}HCD_2CH_3} \longrightarrow \overset{\mathrm{rh^{III}D}}{\mathrm{CH_3CH{=}CDCH_3}} \longrightarrow \mathrm{CH_3CD{=}CHCH_3} + \mathrm{rh^{I}} + \mathrm{D^+} \qquad (13)$$

some explanation is required. The most likely source of $C_4H_6D_2$ is given by eq 14.



$$\mathrm{CH_3\overset{rh^{III}}{C}HCD_2CH_3} \longrightarrow \overset{\mathrm{rh^{III}D}}{\mathrm{CH_3CH{=}CDCH_3}} \xrightarrow{\text{a}} \mathrm{CH_3CHD{-}\overset{rh^{III}}{C}DCH_3} \xrightarrow{\text{2 steps}} \mathrm{CH_3CD{=}CDCH_3} + \mathrm{rh^{I}} + \mathrm{H^+} \qquad (14)$$

The increment in $C_4H_6D_2$ content of *trans*-2-butene as compared with *cis*-2-butene suggests that the latter may be displaced more slowly from its rhodium(III) complex. If this were so, deuterium could be reincorporated (eq 14a) to a greater extent in coordinated *cis*-2-butene to give, following stereospecific elimination, d_2-*trans*-2-butene.

(c) A comparison of the composition of the mixture of $CH_3CD_2CH{=}CH_2$, $CH_3CHDCH{=}CH_2$, and $CH_3CH_2CH{=}CH_2$ before and after partial isomerization provides evidence for an isotope effect in the elimination of hydride. This is apparent in Table VI which shows that about 50% more $CH_3CH_2CH{=}CH_2$ is isomerized than $CH_3CD_2CH{=}CH_2$ although the reactant contains about three times as much of the latter.

Table VI. Isotope Effect in Isomerization of $CH_3CD_2CH{=}CH_2$

	Mole % in substrate	Mole % in product	Mole % reacted
$CH_3CH_2CH{=}CH_2$	17.6	9.4	8.2
$CH_3CHDCH{=}CH_2$	26.7	18.2	8.5
$CH_3CD_2CH{=}CH_2$	51.0	45.6	5.4

Although the $CH_3CH_2CH{=}CH_2$ in the mixture of partially deuterated 1-butene was isomerized preferentially, the over-all rate of isomerization of the mixture was only slightly less than that of pure $CH_3CH_2CH{=}CH_2$ ($k_{\mathrm{CH_3CH_2CH{=}CH_2}}/k_{\text{mixed deuterio-1-butene}} \approx$ 1.1).

Rates of Reaction Steps. The competing reactions involved are summarized in Scheme VI but only incomplete qualitative comparisons of the various

Scheme VI. Competing Reactions in Olefin Isomerization

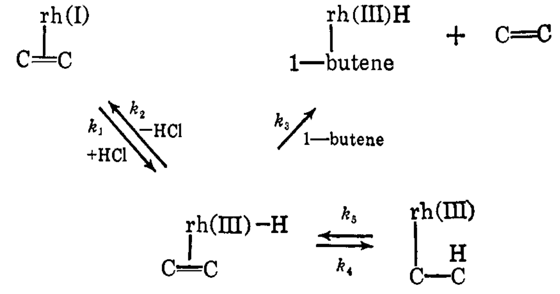


Table VII. Rate of Butene Isomerization (at 0°)

No.	Concn, M Rh	HCl	LiCl	Solvent	$k \times 10^3$ min^{-1} (ml of cat. soln)$^{-1}$	k_H/k_D
			(A) 1-Butene			
1	0.0025	0.2	0	CH_3OH	2.3	
2	0.0063	0.2	0	CH_3OH	8.0	
3–5	0.050	0.1	0	CH_3OH	30,30,36	
6–7	0.050	0.1	0	CH_3OD	20,30	1.3
8–9	0.039	0.02	0.25	CH_3OH	4.5,4.8	
10	0.039	0.02	0.25	CH_3OD	3.5	1.3
11	0.052	0.05	0.13	CH_3OH	8.5	
12	0.052	0.05	0.13	CH_3OD	6.0	1.4
13–14	0.058	0.02	0.25	CH_3OH	9.1,12	
15–16	0.058	0.02	0.25	CH_3OD	7.3,9.2	1.3
17	0.077	0.04	0.25	CH_2OH	20	
18–19	0.077	0.04	0.25	CH_3OD	22,23	0.89
			(B) *cis*-2-Butene			
20	0.00064	0.04	0	CH_3OH	4.5	
21	0.0013	0.04	0	CH_3OH	7.4	
22	0.0012	0.002	0.1	CH_3OH	5.3	
23	0.013	0.2	0	CH_3OH	27	
24	0.075	0.06	0	CH_3OH	10	
25–26	0.0012	0.004	0.1	CH_3OH	2.9,3.2	
27–28	0.0012	0.004	0.1	CH_3OD	0.60,0.55	5.3
29–30	0.0012	0.004	0.25	CH_3OH	4.1	
31	0.0012	0.004	0.25	CH_3OD	1.3	3.1
			(C) *trans*-2-Butene			
32	0.0124	0.2	0	CH_3OH	8.2	

rates can be proposed. At least some are so nearly equal that the order depends upon the specific olefin involved. The fact that the concentration of rhodium(III) species increases only slowly with increasing concentration of HCl (Figure 1) suggests that $k_2 > k_1$ and it is possible that k_1 is the rate-determining step for it is very slow at −25°.[9b]

When C=C is 1-butene, the tracer experiments suggest the following relationships: k_4 (Rh on terminal C) (≈ 15) > k_3 (≈4) > k_4 (Rh on internal C) (≈1) > k_2.

When C=C is 2-butene, $k_4 > k_2 > k_3$. The solvent isotope effect is greater for isomerization of *cis*-2-butene than 1-butene (k_H/k_D *ca.* 4.2 *vs.* 1.3) but the pertinence of this information to the mechanism is not clear.

Rhodium Hydride. The most serious deficiency in the evidence for the mechanism described here is the failure despite attempts under a variety of conditions to detect a rhodium hydride in the reaction mixture by its characteristic nmr absorption.[21] However, we have not been able to formulate other attractive structures containing hydrogen and coordinated olefin which might be expected to exchange olefin faster than hydrogen. Possibly hydride concentration is too low or the rate of addition to olefin is fast enough to perturb the signal.

Experimental Section

The 1-butene used in this work was Matheson Co. CP grade. Vpc analysis indicated it was over 99% pure and contained 0.16 *cis*- and 0.12% *trans*-2-butene. *cis*- and *trans*-2-butenes were Phillips pure grade and were over 99% pure. *cis*-2-Butene contained 0.01% 1-butene and 0.05% *trans*-2-butene. Rhodium chloride was purchased from Engelhard Ind. and CH_3OD was obtained from Merck Sharpe and Dohme of Canada. Tetrakis(ethylene)-μ,μ'-dichlorodirhodium(I)[10] and acetylacetonatodiethylenerhodium(I)[11] were prepared by reported procedures. Other reagents were commercial analytical reagent grade. All were used without purification.

Rate Studies and Effect of Competing Olefins. The apparatus is shown in Figure 5. It consisted of a 25-ml stirred reaction flask (F) and a sample collector (C) with a capacity of about 5 ml. In a typical experiment F was charged with 2.00 ml of CH_3OH containing 0.0030 g of acacRh$(C_2H_4)_2$ and C was sealed to it with a polyphenylene oxide resin. F was frozen in liquid nitrogen and evacuated, and 2.00 ml of HCl (gas) was added. The reaction mixture was warmed to 25° for 3 min (to activate the catalyst), then chilled in liquid nitrogen, and 300 ml of 1-butene (gas) was added. (In some experiments other olefins were added to the reaction mixture at this point.)

A leveling bulb (L) was attached to C, and F was placed in a constant temperature bath at −23° (CCl_4 slush), −10° (ice–acetone slush maintained by occasional addition of solid carbon dioxide), or 0° (ice and water). Analytical samples were collected as follows. First C was swept out in order to get a representative sample. To do this S_1 and S_2 were closed and C was evacuated through R. R was clamped off close to C, and S_1 was opened to admit a sample of the solution through the capillary inlet of C which extended beneath the surface of the reaction mixture of F. The sample evaporated as it rose in the capillary so that a gaseous sample passed through S_1. S_1 was closed and R was opened for about 10 sec. Next the sample was collected. R was clamped off and S_1 was opened to admit a butene mixture into C. S_2 was opened. The gas sample was compressed by raising L. A portion was withdrawn by a hypodermic syringe inserted in R and transferred to a vpc column. Conditions for separating butenes are described later. No reaction solution was held in the capillary between collection of samples. It was forced out by butene which evaporated when S_1 was closed.

Since about 3% of the butene charged was withdrawn in each sampling operation and as many as ten samples were withdrawn, the concentration of olefin in the reaction mixture changed appreciably during reaction. Rates were not corrected for change in concentration as a consequence of sampling.

Generally catalytic activity of solutions remained high but in some experiments, particularly with acacRh$(C_2H_4)_2$ and 1-butene at 0°, the rate of isomerization decreased in a way that corresponded to catalyst deactivation. The cause was not discovered.

Calculations. Analyses gave the composition of the mixture of butenes at various times. Isomerization was treated as a reversible,

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[21] W. P. Griffith and G. Wilkinson, *J. Chem. Soc.*, 2757 (1959); R. D. Gillard and G. Wilkinson, *ibid.*, 3594 (1963); J. A. Osborn, R. D. Gillard, and G. Wilkinson, *ibid.*, 3168 (1964).

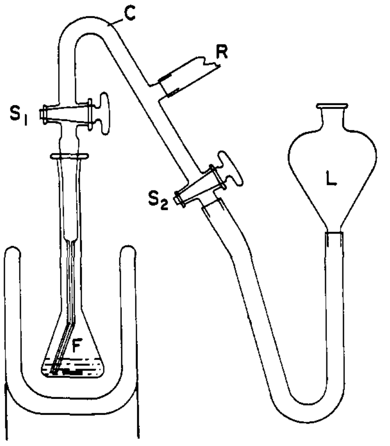

Figure 5. Apparatus for butene isomerization.

first-order reaction with the rate described by the equation $\ln (A_0 - A_e)/(A - A_e) = (k + k')t$,[13] where A is the per cent of butene to be isomerized (A_0, at time 0; A_e, at equilibrium; A, at time t). A_e was calculated from published data.[16]

A typical result is shown in Figure 6. Results of some other experiments are given in Table VII.

Isomerization–Deuteration. In a typical experiment the reaction vessel consisted of a 25-ml erlenmeyer flask (containing a Teflon-covered magnetic stirrer) to the neck of which was sealed a 15-cm length of 8-mm tubing. The flask was charged with a solution of 0.02 g of $acacRh(C_2H_4)_2$ (0.08 mmole) in 2.00 ml of CH_3OD (70 mmoles of D). The solution was frozen in liquid nitrogen, the flask was evacuated, and 25 ml of DCl gas (1 mmole) was added by gas buret. With exclusion of air, the mixture was warmed to 25° for 5 min to activate the catalyst and convert a substantial part of the coordinated ethylene to butenes.[9b] The flask was again chilled in liquid nitrogen and 200 ml of 1-butene (8 mmoles) was added. (Other olefins were added at this point in some experiments.) The neck of the cold, evacuated flask was fused and the flask was transferred to a constant temperature bath. (At various times, refluxing NH_3 (−33°), refluxing CH_3Cl (−24°), CCl_4 slush (−23°), and the ice (0°) were used.) Following reaction, the mixture of butenes was pumped from the reaction mixture (which was kept at or below the nominal reaction temperature). The butenes were analyzed and separated by vpc. For this purpose a 6-ft column packed with ethyl N,N-dimethyloxalamide on 60–80 mesh acid-washed firebrick was employed at a temperature of about 0° and a helium flow rate of 45 ml min^{-1}. The approximate retention times are 1 min (ethylene), 4 min (1-butene), 5 min (*trans*-2-butene), and 6 min (*cis*-2-butene). Over 90% of the butene charged was recovered for analysis; tests in which gas mixtures of typical, known compositions were recovered from 0.5 *M* ethanolic HCl show that the composition of the reaction mixture is given by the peak areas with an error of less than 2%.

A similar procedure was used in the isomerization–deuteration of 2-butenes.

Samples of the individual deuterated butenes separated by vpc were collected and analyzed by mass spectroscopy. In some experiments low-voltage mass spectrograms were the basis for calculation of the extent of deuteration and in others spectra at 70 ev were used. In three experiments, parallel caculations using low-voltage patterns checked the calculations based on the 70-ev spectra with an average discrepancy of 0.8% and a maximum of 3%. Peak heights at mass/charge ratios 53 to 58 were used for C_4H_8, 54 to 59 for C_4H_7D, 55 to 60 for $C_4H_6D_2$, 56 to 61 for $C_4H_5D_3$, and 57 to 62 for $C_4H_4D_4$. It was assumed that the distribution of peak heights at different *m/e* ratios were the same for the deuteriobutenes as for C_4H_8. Using distributions for *m/e* determined for the individual C_4H_8 isomers, simultaneous equations were written relating the amounts of butenes from C_4H_8 to $C_4H_4D_4$ to the peak heights for *m/e* from 53 to 62 and these were solved for the composition of the mixture.

About 20% of the 1-butene was isomerized (with corresponding H–D exchange) in 6 hr at −23° in the reaction mixture just described. If, in addition, 25 ml of C_2H_4 gas was added, only 0.5% isomerization and H–D exchange of 1-butene occurred in 6 hr but 10% of ethylene hydrogen was replaced by deuterium.

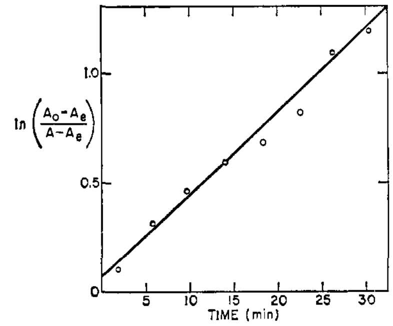

Figure 6. Rate of isomerization of 1-butene.

At −33° there was no detectable isomerization or deuteration of 1-butene in 17 hr. When $CHCl_3$ was used as solvent instead of CH_3OD, 75% of the 1-butene was isomerized after 1 hr at −33°.

$CH_3CD_2CH{=}CH_2$ was synthesized according to eq 15–18 by procedures analogous to those employed by Davies[6a] in preparing $C_5H_{11}CD_2CH{=}CH_2$.

$$CH_3COOC_5H_{11} + 4CH_3COOD + 4Na \xrightarrow{\text{ether}} CH_3CD_2OD + C_5H_{11}OD + 4CH_3COONa \quad (15)$$

$$CH_3CD_2OD + HBr \longrightarrow CH_3CD_2Br \quad (16)$$

$$CH_3CD_2Br + NaC{\equiv}CH \xrightarrow{\text{liq } NH_3} CH_3CD_2C{\equiv}CH \quad (17)$$

$$CH_3CD_2C{\equiv}CH + (NH_4)_2SO_4 + 2Na \xrightarrow{\text{liq } NH_3} CH_3CD_2CH{=}CH_2 + Na_2SO_4 + 2NH_3 \quad (18)$$

Difficulty was encountered only with the first reaction. In our hands it persistently yielded deuterioethanol which, according to nmr analysis, had between 25 and 35% protium on the α carbon and thus accounted for the protium on C_3 in $CH_3CD_2CH{=}CH_2$. In addition, the reaction was slow. Attempts to simplify isolation of CH_3CD_2OH by using toluene or diglyme as solvent instead of ether were unsuccessful because little reaction occurred below −5°, the recommended temperature for accomplishing the reduction.

Procedures for isomerizing $CH_3CD_2CH{=}CH_2$ and analyzing the products were the same as those used with $CH_3CH_2CH{=}CH_2$. The rates of isomerization of $CH_3CH_2CH{=}CH_2$ and $CH_3CD_2CH{=}CH_2$ are nearly equal (Table VIII).

Table VIII. Isomerization of $CH_3CD_2CH{=}CH_2$[a] and $CH_3CH_2CH{=}CH_2$

No.	Concn, *M*: Rh	HCl	LiCl	Olefin	$k \times 10^3$ min^{-1} (ml of cat. soln)$^{-1}$
1	0.0058	0.04	0.25	$CH_3CH_2CH{=}CH_2$	22
2, 3	0.0058	0.04	0.25	$CH_3CD_2CH{=}CH_2$[a]	21, 29
4–6	0.05	0.1	0	$CH_3CH_2CH{=}CH_2$	30, 30,36
7	0.05	0.1	0	$CH_3CD_2CH{=}CH_2$[a]	34

[a] $CH_3CD_2CH{=}CH_2$ used in these experiments had 35% protium on C_3.

Spectra of Catalyst Solutions. Deoxygenated solvents were employed and solutions were prepared and charged into sealed optical cells in an ethylene atmosphere. $[(C_2H_4)_2RhCl]_2$ was dissolved in sufficient 0.5 *M* ethanolic HCl to give a solution which was 0.075 *M* Rh and this was diluted with ethanolic HCl of requisite strength to provide a series of solutions which were 0.0075 *M* in Rh and from 0.05 to 3.0 *M* in HCl.

Spectra were recorded with 1-cm cells using a Perkin-Elmer 4000 A spectracord. The curves reproduced in Figure 1 show solutions 6 hr old. Nearly identical absorptions are obtained with solutions which are 1 or 24 hr old.

An nmr tube was charged with 0.2 g of $[(C_2H_4)_2RhCl]_2$ (0.5 mmole) and 0.6 ml of methanol. The tube was chilled in liquid nitrogen and evacuated, and 50 ml of HCl was added. The tube was sealed and warmed to 25°; after 2 hr, the spectrum was recorded using a Varian A-60 nmr spectrometer. The spectrum contained a pattern of sharp absorptions between 73 and 82 cps which is characteristic of a mixture of *cis-* and *trans-*2-butene, and broad, smooth absorption between 20 and 70 cps which is attributed to alkyl proton. The ratio of integrated absorptions was 1:1.7.

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Polypeptides with Known Repeating Sequence of Amino Acids. Synthesis of Poly-L-glutamyl-L-alanyl-L-glutamic Acid and Polyglycylglycyl-L-phenylalanine through Pentachlorophenyl Active Ester[1]

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Abstract: A general method for the synthesis of polypeptides with known repeating sequence of amino acids using pentachlorophenyl active esters was developed in this laboratory, and the applicability of this method is demonstrated by the synthesis of poly-Glu-Ala-Glu (XVIII) and poly-Gly-Gly-Phe (XVI). The following advantages in using active pentachlorophenyl esters were demonstrated experimentally: (a) pentachlorophenyl esters make a good combination with *t*-butyl and N-carbobenzoxy protecting groups when peptides with trifunctional amino acids are polymerized; in contrast with thiophenyl and *p*-nitrophenyl esters, the N-carbobenzoxy protecting group is selectively removed under controlled hydrogenation conditions leaving the pentachlorophenyl and *t*-butyl groups intact; (b) the resulting peptide pentachlorophenyl ester hydrochlorides as well as the intermediate active esters are easier to purify since they are frequently higher melting compounds than other active esters (Table I); (c) the very active tripeptide pentachlorophenyl esters polymerized fast in DMSO or DMF to high molecular weight polypeptides which proved to be in a practical sense (98 ± 2%) optically pure. Optically pure tripeptide active ester VII has been prepared by lengthening the peptide chain (a) from the N-terminal residue, (b) from the C-terminal residue through the active esters, and (c) by coupling of N-carbobenzoxy-γ-*t*-butyl-L-glutamyl-L-alanine azide, made from hydrazide XV, with γ-*t*-butyl-L-glutamic acid pentachlorophenyl ester hydrochloride (XIII). This indicated that coupling through pentachlorophenyl esters yielded, after purification, optically pure tripeptide active esters. Highly purified HCl·H-Glu(OBu-*t*)-Ala-Glu(OBu-*t*)-OPCP (VIII) and HCl·H-Gly-Gly-Phe-OPCP (XV) gave the corresponding polypeptides XVII and XVI in good yields. Removal of the *t*-butyl protecting groups with 90% trifluoroacetic acid afforded the water-soluble polypeptide XVIII which, after extensive dialysis, gave an approximate weight average molecular weight of 25,000 and a number average molecular weight of about 16,000. The ratio of M_w/M_n was 1.6, which is indicative of a not too heterogeneous polymer. The possibility of transpeptidation of α-glutamyl residues during the removal of *t*-butyl groups was investigated. Model α- and γ-tripeptides VI and XXXII were treated with trifluoroacetic acid, and it was found within 1% accuracy that transpeptidation did not occur. The free poly-Glu-Ala-Glu was not antigenic in contrast with the random polypeptide $Glu_{60}Ala_{40}$.

There has been a great demand for high molecular weight polypeptides with known repeating sequences of amino acids,[2] especially for those which are water soluble and contain trifunctional amino acids. These polypeptides would be expected to resemble proteins more closely than those consisting of only difunctional amino acids. In 1958, Katchalski, in his excellent review,[2a] summarized the work pertaining to the syntheses of such polypeptides. Practically all the methods which were developed for the stepwise synthesis of oligopeptides were tried for the synthesis of polypeptides with known repeating sequences of amino acids; however, none of these methods satisfy the various requirements for the preparation of such polymers. Since 1954 we have been working on these problems,[3] and the main difficulty in using the established coupling methods,[4] *e.g.*, mixed anhydride or dicyclohexylcarbodiimide, is the undesired side reactions which lead to early termination of polymerization. On the other hand, the thiophenyl active ester method which was used first by Wieland and Bernhard to

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[1] (a) A part of this work was presented at the IUPAC Meeting, Kyoto, April 1964, and communicated by J. Kovacs and A. Kapoor, *J. Am. Chem. Soc.*, **87**, 118 (1965). (b) This is the fourth in a series of papers concerned with polypeptides with known repeating sequence of amino acids; for the previous paper in this series see J. Kovacs and B. J. Johnson, *J. Chem. Soc.*, 6777 (1965).

[2] (a) E. Katchalski and M. Sela, *Advan. Protein Chem.*, **13**, 243 (1958); (b) C. H. Bamford, H. Elliott, and W. E. Hanby, "Synthetic Polypeptides," Academic Press Inc., New York, N. Y., 1956; (c) E. R. Blout, "Polyamino Acids, Polypeptides and Proteins," M. A. Stahmann, Ed., The University of Wisconsin Press, Madison, Wis., 1962, pp 3–11; (d) P. H. Maurer, *Progr. Allergy*, **8**, 1 (1964).

[3] (a) J. Kovacs, ref 2c, pp 37–47; (b) V. Bruckner and J. Kovacs, *Acta Chim. Acad. Sci. Hung.*, 12, 363–404 (1957), a summarizing review; (c) V. Bruckner, M. Kajtar, J. Kovacs, H. Nagy, and J. Wein, *Tetrahedron*, **2**, 211 (1958).

[4] (a) M. Goodman and G. W. Kenner, *Advan. Protein Chem.*, **12**, 465 (1957); (b) N. F. Albertson, *Org. Reactions*, **12**, 157 (1962).