[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF SOUTHERN CALIFORNIA]

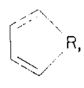
The Stereochemistry and Mechanism of the Diels–Alder Reaction. An "Internal" Mechanism for the Interconversion of *endo-exo* Isomers[1,2]

BY JEROME A. BERSON, ROSALIE D. REYNOLDS AND WILLIAM M. JONES

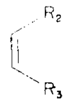
RECEIVED JULY 20, 1956

When the *endo*-cyclopentadiene–maleic anhydride adduct, radioactively labeled in the carbonyl carbons, is heated with an equimolar quantity of inactive maleic anhydride, the *exo* isomer is formed, and has an activity higher than that theoretically possible if it were formed entirely by a dissociation-recombination mechanism. The most likely explanation for the "internal" mechanism involves an intermediate complex or solvent-caged aggregate.

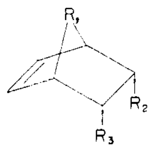
When a cyclic diene (I) reacts with a dienophile (II), the stereochemistry of the product can be either *endo* (IIIa) or *exo* (IIIb).[3] *exo*-Products are usually formed at slower rates than their *endo* isomers, and consequently are infrequently observed in diene additions carried out at low temperatures and/or short reaction times. Nevertheless, the *exo* isomers usually are thermodynamically the more stable and, under equilibrating conditions or at temperatures sufficiently high to overcome the unfavorable activation energy for their formation, accumulate at the expense of the *endo* isomers.[4] A detailed description of the events that occur in the interconversion of *endo–exo* isomers is of importance to a more complete understanding of diene addition processes. In the present paper, we report a study of the interconversion of the stereoisomeric cyclopentadiene–maleic anhydride adducts, N and X.



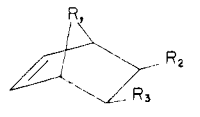
I



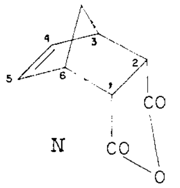
II



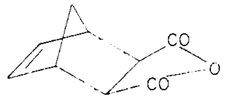
IIIa



IIIb



N



X

The mechanism of the interconversion of *endo*- to *exo*-adducts has been represented as (A), a direct conversion, not involving dissociation into kinetically free fragments,[4g] and (B), a retrogression of the *endo*-adduct to the addends, which then recombine to give the *exo* isomer.[4b,e] When combined with the only remaining formal possibility, *i.e.*, that *both* processes can occur simultaneously, these mechanisms, applied to N and X, may be expressed in a set of cyclic coupled equilibria (equation 1) (M = maleic anhydride, C = cyclopentadiene)

$$X \underset{k_6}{\overset{\overset{A}{k_5}}{\rightleftarrows}} N \underset{\underset{B_1}{k_2}}{\overset{k_1}{\rightleftarrows}} M + C \underset{k_3}{\overset{\overset{B_2}{k_4}}{\rightleftarrows}} X \qquad (1)$$

Our approach involved the use of radioactive tracers. N was prepared, radioactively labeled in the carbonyl carbons, by the reaction of cyclopentadiene with maleic anhydride-1-C^{14}, and its conversion to X was studied in the presence of an equimolar quantity of added non-radioactive M. Since no C was added to the system, the only possible sources of C were N and X. The reactions were carried out in decalin solution at the boiling point (188.5°). (Craig[4g] had shown that N and X were interconvertible at 190° in the molten state.) *A priori*, one of the following sets of circumstances was anticipated: (i) exchange of M between radioactive N and the surroundings would be very rapid compared to all other processes. In this case, X would have the statistical distribution of isotope, *i.e.*, 50% of the activity of the N starting material, regardless of the mechanism of the conversion. However, the observation of statistical isotope distribution in X would not necessarily imply that exchange was so rapid as to have obliterated traces of the mechanism (*vide infra*). (ii) Exchange of M from radioactive X would be very rapid. (iii) Exchange of M would not be fast enough to conceal the mechanism. (a) If the conversion of N to X went by path A only, X would have greater than 50% of the activity of starting N. (b) If the conversion went by path B_1–B_2 only, X would have less than 50% of the activity of starting N. (c) If the conversion went by both paths, X could have an activity greater than, less than, or (fortuitously) equal to statistical, but the occurrence of both paths could be demonstrated and their relative importance could be calculated, given a knowledge of the rate of exchange of M between N and X and the surroundings, and of the rate of formation of X.

The experimental section describes studies of the rates of exchange of N and of X with outside M and of the rate of formation of X, as well as

---

[1] Sponsored by the Office of Ordnance Research, U. S. Army.

[2] For a preliminary report, see THIS JOURNAL, **77**, 4434 (1955).

[3] K. Alder, G. Stein and E. Rolland, *Ann.*, **525**, 247 (1936).

[4] (a) K. Alder and G. Stein, *Angew. Chem.*, **50**, 514 (1937); (b) R. B. Woodward and H. Baer, THIS JOURNAL, **66**, 645 (1944); (c) K. Alder, F. W. Chambers and W. Trimborn, *Ann.*, **566**, 27 (1950); (d) K. Alder and R. Ruhmann, *ibid.*, **566**, 1 (1950); (e) K. Alder and W. Trimborn, *ibid.*, **566**, 58 (1950); (f) H. Kwart and I. Burchuk, THIS JOURNAL, **74**, 3094 (1952); (g) D. Craig, *ibid.*, **73**, 4889 (1951); (h) J. A. Berson and R. Swidler, *ibid.*, **75**, 1721 (1953); **76**, 4060 (1954); (i) D. Craig, J. J. Shipman, J. Kiehl, F. Widmer, R. Fowler and A. Hawthorne, *ibid.*, **76**, 4573 (1954); (j) C. S. Rondestvedt and C. D. Ver Nooy, *ibid.*, **77**, 4878 (1955).

determination of the activity of X after given periods of reaction.

Experimental Details and Calculations

Preparation of Materials.—Decalin was purified from a technical grade material by preliminary distillation, exhaustive washing with concentrated sulfuric acid, then washing with water, aqueous sodium carbonate and finally with water. This material was then dried over magnesium sulfate and finally distilled twice from sodium. A fraction boiling at 191° was collected. Maleic anhydride-1-C^{14} was supplied by Nuclear Instrument and Chemical Co., Chicago, Ill., on allocation from the Atomic Energy Commission. Radioactive N and X were prepared by the method previously described,[5] and recrystallized from benzene to constant activity and melting point.

Counting Techniques.—Apparent activities were determined with a Nuclear Instrument Model D46A Q-gas flow detector using either a Nuclear Model 162 binary scaler or a Berkeley decimal scaler. Samples were counted in substance as "infinitely thick" films by the technique previously described.[5] Background rates were about 35–40 c./min. To reduce statistical error, total counts recorded on each count of a given sample were always greater than 10,000. With the sample to background count ratios encountered in the present work, the statistical standard error was about 1%.[6] Reproducibility of counting rates on a given sample was always better than ±1% average deviation. Apparent activities of a given sample seldom fluctuated more than ±1% with storage. Nevertheless, to minimize instrument fluctuations, comparisons of theoretical significance were always made by counting starting material and product during the same period of operation of the detector, usually within an hour of each other. Backgrounds were determined before and after a set of counts.

Exchange Experiments.—The reaction vessel was a 500-cc. three-necked flask, fitted with a condenser and a thermometer dipping into the solvent. The condenser outlet was protected from moisture with a calcium chloride tube. The appropriate quantity of purified decalin was placed in the flask and brought to reflux by heating with an oil-bath at 206–213°. A 10-cc. beaker containing a mixture of radioactive N (or X) and inactive M was inserted into the solvent with the aid of a long wire and the flask was immediately re-stoppered. Refluxing ceased only for a few seconds, and time zero was noted when refluxing began again. The temperature during the runs was 188.5 ± 0.5°. After an appropriate time, the reaction was quenched by removing the oil-bath. The decalin was removed by distillation *in vacuo* at 41–42° and 3 mm. (bath below 80°). The residue was fractionally crystallized from benzene. X was easily isolated from the head fractions when present in high concentration, but isolation of N often required twelve to fourteen recrystallizations of the combined tail fractions. The purity of materials was followed roughly by melting point[4g] and final evidence of purity was obtained by recrystallization to constant activity. The pyrolysis procedure was duplicated in detail for each run. The results of the exchange experiments are given in Table I. The values for 10 and 7 minutes (runs 200, 201 and 202) were determined on samples isolated from the same reaction mixtures as runs with the same numbers in Table III. The uncertainty in the fractions of residual activity is about ±0.01, and results from a combination of errors calculation assuming a standard error of 1% in the mean of the individual counts on each sample counted. Apparent activities of starting material were between 1000 and 3000 c./min.

TABLE I

EXCHANGE EXPERIMENTS AT 188.5° WITH RADIOACTIVE N AND X AND INACTIVE M[a]

Run	Starting cpd.	Time, min.	Fraction of activity remaining[b]
82	X	60	0.83
88[c]	X	60	.52
101	X	30	.88
96	N	30	.51
200	N	10	.54
201	N	7	.60
202	N	7	.62

[a] Starting concentrations: 0.102 *M* radioactive N or X, 0.102 *M* M unless otherwise indicated. [b] Activity of substance after re-isolation/its starting activity, both corrected for background. [c] 0.0052 mole each of X and M, molten, no solvent. Heated at 189.5° in a constant temperature vapor bath.

Analysis for X.—The rapid exchange of N observed in Table I made it necessary to determine the activity of X at short reaction times, since N reached statistical isotopic distribution soon after 10 minutes reaction. Unfortunately, we were unable to isolate X directly after short reaction times, and we resorted to isotope dilution techniques. In equation 2, X_t is the weight of X formed after time t, α_t is its activity, X_s and α_s are the weight and activity of carrier X added, and α_r is the activity of recovered X.

$$\alpha_r = \frac{\alpha_s X_s + \alpha_t X_t}{X_s + X_t} \qquad (2)$$

X_t was first determined for varying periods of reaction using radioactive X as carrier. (We also investigated the possibility of analyzing for X by infrared spectrophotometry. This appeared to be feasible, but required the use of solvents other than decalin, since the latter absorbed strongly in the analytical region. Removal of decalin from the reaction mixtures and replacement with other solvents would have introduced a number of complications, *e.g.*, the problem of contamination of the residues with decalin and the possibility of chemical fractionation of the rather volatile N and X during evaporation. These difficulties were avoided by use of the isotope dilution procedure.) The reactions were carried out using exactly the same procedure as in the exchange runs, except that once the reaction mixture was quenched, the appropriate quantity (X_s) of carrier X was added to the reaction flask. To ensure complete mixing of carrier X with X formed in the reaction, a little benzene was added if necessary to give a clear solution. Isolation of X was then accomplished as above. The results are given in Table II. The indicated uncertainty is that resulting from the standard error of 1% in the activity determinations. A reproducibility check is given by the duplicate runs 212 and 213.

TABLE II[a]

EXTENT OF THE N → X CONVERSION AT SHORT REACTION TIMES AS DETERMINED BY ISOTOPE DILUTION

Run	Time, min.	Starting weight N_0, g.	X_s, g.	α_s, c./min.	α_r, c./min.	$100X_t/N_0$[b]
210	3	3.0006	1.7148	2612	2343	6.3 ± 0.8
211	7	3.0021	1.6996	2892	2344	13.0 ± 1
212	10	3.0000	1.7012	2612	2051	15.3 ± 0.7
213	10	3.0003	1.7071	2611	2073	14.7 ± 0.7

[a] Starting concentrations: 0.102 *M* N and M in decalin. [b] Calculated from equation 2, with $\alpha_t = 0$.

Determination of Activity of X.—With X_t now known, α_t could be determined by repeating the experiment under identical conditions, adding inactive X as carrier, re-isolating X, determining α_r and calculating α_t from equation 2.

The results reported previously[2] for 3 and 10 minutes were obtained using radioactive X as carrier. These agreed qualitatively with those reported here but, as a referee has pointed out, due to the fact that α_t is obtained as small difference between large numbers when radioactive carrier is used, the values have a large uncertainty. The 7- and 10-minute results of Table III were obtained using inactive carrier. Values of α_t are given only to the nearest significant figure, the indicated uncertainty being that resulting from a combination of errors calculation using the uncertainty in X_t from Table II and a 1% standard error in α_s and α_r. Table III also lists results on the activity of X (essentially statistical distribution) at longer reaction times, in which circumstances X_t was sufficiently large to allow determination of α_t to be made on directly isolated samples, without recourse to isotope dilution procedures. Reproducibility

---

(5) J. A. Berson and W. M. Jones, THIS JOURNAL, **78**, 6045 (1956).

(6) M. Calvin, C. Heidelberger, J. C. Reid, B. M. Tolbert and P. E. Yankwich, "Isotopic Carbon," John Wiley and Sons, Inc., New York, N. Y., 1949, pp. 283–291.

TABLE III[a]

ACTIVITY OF X FORMED FROM INITIALLY RADIOACTIVE N AND INACTIVE M

Run	Time, min.	β_0, c./min.	X_s, g.	α_s, c./min.	α_r, c./min.	α_t, c./min.	α_t/β_0
79	60	1790	....	..	913[b]	913	0.51
95	30	1787	....	..	899[b]	899	.50
200[d]	10	3017	1.7000	0	331	1600 ± 100[c]	.52 ± 0.03
201[d]	7	2981	1.7002	0	169	900 ± 70[c]	.30 ± .02
202[d]	7	3003	1.6997	0	203	1100 ± 80[c]	.37 ± .03

[a] Starting concentrations: 0.102 *M* radioactive N of activity β_0, 0.102 *M* M in decalin. [b] Determined on directly isolated samples of X. [c] Calculated from equation 2, using values of X_t from runs at corresponding times in Table II. [d] Same reaction mixture as the run with the same number in Table I.

was checked by duplicate determinations at 7 minutes (runs 201 and 202). The spread between the theoretically significant quantities α_t/β_0 at 7 minutes for the two runs does not appear to be significantly different from the limits imposed by the statistical counting error.

Controls.—The radioactivity assays of Tables I–III were carried out by counting N or X in substance as "infinitely thick" samples. It was necessary to show that the counting rates so determined were directly proportional to specific activities and thus that activities of X so determined could be directly compared with activities of N. This was done by demonstrating that radioactive N (β = 1882 ± 10 c./min.), when heated at 190° in the absence of M, gave X with the same activity (α = 1887 ± 5 c./min.). Further, when radioactive X of activity α_0 was diluted with non-radioactive X, the assay method reproduced the gravimetric composition with satisfactory accuracy (Table IV) in the range of apparent activities observed in the experiments of Tables I–III.

TABLE IV

CONTROL EXPERIMENTS ON ISOTOPE DILUTION OF X[a]

α_0	α_d	$100\ X_0/(X_0 + X_s)$	$100\ \alpha_d/\alpha_0$
868	428	50.0	49.4
868	762	90.0	87.9
1896	960	50.0	50.6
1896	1695	90.0	89.4

[a] A weighed quantity (X_0) of X of activity α_0 mixed with a weighed quantity (X_s) of non-radioactive X and the mixture recrystallized from benzene. Activities determined as in Tables; α_d = activity of re-isolated X.

Since the procedure for working up the reaction mixtures often required protracted manipulations, it was necessary to show that the activities of the components were not being altered by radioactive exchange during isolation. This was done by working up a simulated reaction mixture of active N, inactive X, inactive M and decalin. Starting with N of activity 1837 ± 5 c./min., N was re-isolated, after a 12-stage fractional crystallization, with undiminished activity (1835 ± 2 c./min.), and X was re-isolated with activity indistinguishable from background. These results showed (i) that no detectable exchange occurred during the isolation procedure and (ii) that radioactively labeled N starting material, which had been recrystallized to constant activity, was not contaminated with any appreciable quantity of X, for if as much as 0.5% of active X had been present, the re-isolated X would have had a detectable activity. Point ii becomes important in the sequel.

Calculations.—The activities theoretically to be expected of X arising exclusively by an "internal" mechanism (path A) from N and by an "external" mechanism (path B_1–B_2) were calculated on the basis of the requirement that the X formed by path A during any small increment of time would have the same activity as the average activity of N during that time, and the X formed by path B_1–B_2 would have the same activity as M during that time. The theoretical activities were determined by a graphical interpolation method. Plots were made for the data on (i) the fractional decrease of the activity of N with time (*i.e.*, β_t/β_0 *vs.* time, from Table I) and (ii) the fraction of N converted to X with time (*i.e.*, X_t/N_0 *vs.* time, from Table II). A reaction period of *t* minutes, for which α_t, the activity of X after *t* minutes, was known (*e.g.*, 7 and 10 minutes), was subdivided into arbitrarily small time increments. Values for the average activity of N and for the fraction of the total amount of X formed during each of the time increments were determined by graphical interpolation from the plots. If X_t/N_0 is the fraction of N converted to X in an experimental period, X_1/N_0 the fraction converted during time increment 1, X_2/N_0 during time increment 2, etc., β_0 the original activity of N for the experimental run, β_1 the average activity of N during time increment 1, β_2 during time increment 2, etc., then the activity α_A of X to be expected by the "internal" path (A) is $\beta_1 X_1/X_t + \beta_2 X_2/X_t + \ldots + \beta_i X_i/X_t$. If we neglect the exchange of M between X and the surroundings,[7] and any kinetic isotope effect, the activity of M at any time is simply $\beta_0 - \beta_j$, where β_j is the activity of N at that time. Therefore, the activity α_B of X to be expected by the "external" path (B_1–B_2) is $(\beta_0 - \beta_1)X_1/X_t + (\beta_0 - \beta_2)X_2/X_t + \ldots + (\beta_0 - \beta_i)X_i/X_t$. The theoretical activities depended upon the number and size of the increments taken, especially in the early portion of the reaction periods when β was changing rapidly. However, they reached limiting values when the increments were 0.5 minute, and calculations using a larger number of smaller increments produced no significant change. The theoretical activities were not very sensitive to the uncertainties in the values used in making the plots. Values obtained from plots made from the upper and lower extremes of the data in Tables I and II differed only slightly from those obtained using mean values. A further possible source of error is in the quenching lag associated with the short reaction times. Fortunately, this was almost completely eliminated by determining α_t and β_t for the short runs on samples isolated from the same reaction mixture. Thus, any quenching lag in the determination of α_t was necessarily also present in the determination of β_t. From the rate at which the temperature fell, we estimate the quenching lag at about 30 seconds. We have calculated the theoretical activities (α_A and α_B) from plots in which a full minute lag was allowed (*i.e.*, 3-minute point plotted as four minutes, etc.). The values for α_A and α_B obtained in this way are within the extremes of experimental uncertainty introduced by the statistical counting error. The values for α_A and α_B given in Table V are averages of values obtained from the several described plots. The indicated uncertainties are the approximate deviations from the mean of the most disparate values.

TABLE V

Run	Time, min.	β_t	Activity, counts/minute α_A	α_B	α_t
200	10	3017	2340 ± 100	640 ± 40	1600 ± 100
201	7	2981	2410 ± 60	540 ± 40	900 ± 70
202	7	3003	2480 ± 60	560 ± 40	1100 ± 80

Table V shows that the activity (α_t) of X formed from initially radioactive N and inactive M is consistently higher than that (α_B) expected if it were formed entirely by a simple "external" dissociation–recombination mechanism (path B_1–B_2). We have considered the possibility that the high values for α_t might be caused by contamination of the N starting material with a small percentage of radioactive X. Since the amount of X formed in the short reaction times studied is small, this kind

---

(7) This correction is small at short reaction times (see Table I). Its neglect leads to a slightly more conservative estimate of the relative importance of path A.

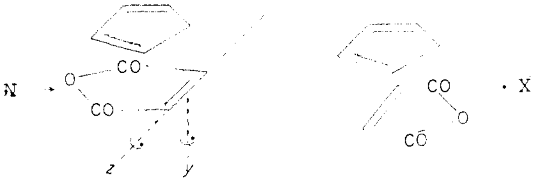
of contamination would lead to an observed activity for the X isolated from the reaction mixture significantly higher than the activity of X actually formed in the reaction. For run 200, the observed α_t (1600 c./min.) could be accounted for if the re-isolated X were a mixture of 60% X formed in the reaction with activity α_B (640 c./min.) and 40% X of activity 3017 c./min. carried through from the starting material as contaminant. Thus, the starting N would have to have been contaminated with about 6% of X. However, we have already shown that our samples of N could not contain more than about 0.5% of X. Contamination with as much as 6% of X would have been unmistakably apparent.[8,9] We conclude that the high values of α_t cannot be accounted for by contamination, and consequently that some of the X formed arises by an "internal" mechanism (path A of equation 1). The fraction (A) of X formed by this path is given by equation 3.

$$A\alpha_A + (1 - A)\alpha_B = \alpha_t \qquad (3)$$

For run 200, $A = 0.5 \pm 0.07$, and for run 202, $A = 0.3 \pm 0.05$.[10] The remainder of the X is formed by path B_1–B_2, which does not discriminate between M free in the system and M originating from N. Cyclopentadiene is able to combine directly with M to give X, despite the theoretically unfavorable[4b,11a,b] arrangement in the transition state.

In path A, X incorporates M that was originally part of N, but does not include any kinetically free M from the bulk of the solution. The possibility that the "internal" mechanism might involve N → X conversion by epimerization *via* enolic species seems to be eliminated by Craig's finding[4g] that the isomerization, at least in the molten state, is not catalyzed by acids or bases. Craig[4g] has proposed, on grounds other than ours, that the N → X conversion is "internal," and has suggested that this occurs by cleavage (presumably homolytic) between C.1 and C.6 of N, hydrogen shift from C.7 to C.4, and finally, re-establishment of a bond between C.1 and C.5. In the absence of a position-labeling experiment, there is no direct evidence against this mechanism. We consider it unlikely, however, mainly on the grounds that resonance would flatten the five-membered ring C.3, C.4, C.5, C.6 and C.7, and thereby make the C.4–C.7 distance too great (>3 Å.) to allow the postulated hydrogen shift.

All of the remaining alternatives for path A require the stereochemical equivalent of equation 4, *i.e.*, fragmentation of N into the component addends, rotation of one addend with respect to the other (for example, of M about either of the axes *y* or *z*), and recombination of the *original partners*, without intervention of outside M.



(4)

This might be caused by (i) diffusion-controlled "secondary recombination"[12] of addends (M and C), originally partners in an N molecule, before either encounters C or M, respectively, from the bulk of the solution; (ii) conversion of N to a complex in which M and C can rotate with respect to each other, followed by recombination in either stereochemically possible sense; (iii) a "cage effect,"[13] involving imprisonment of the fragments from a given molecule of M by solvent molecules, and consequent "primary recombination" of original partners within the cage.

The "secondary recombination" (process i), being diffusion-controlled, can be important only if the probability of reaction at each encounter is high, *i.e.*, if there is essentially no activation energy associated with the recombination. Although the activation energy for the addition of M to C is unknown, it can hardly be less than about 10 kcal./mole, by analogy to other diene addition processes.[11b] This is entirely too high to allow any appreciable portion of path A to result from "secondary recombination."

On the basis of our results, the complex is indistinguishable from the caged aggregate. Even on conceptual grounds, the distinction is somewhat arbitrary. However, one might characterize the complex as a valley in a potential energy surface, deriving stability from electronic interaction between the fragments. The most favorable arrangement would probably be one in which the fragments lie face to face, in nearly parallel planes.[4b,11a,b] As a distinct alternative, the aggregate of two fragments in a cage might have no particular steric orientation.[14] We are presently engaged in isom-

---

[8] In the control experiment in which active N (β = 1837 c./min.) was mixed with inactive X and the X re-isolated, the latter would have had an activity of about 150 c./min. (found nil, *i.e.*, background ±2 c./min.); the N re-isolated would have had an activity of about 1780 c./min. (found 1835 c./min).

[9] (a) The above calculations were made on the assumption that the inactive N was not contaminated, *i.e.*, that the values of X_t/N_t in Table II are accurate. We have repeated the calculations by a trial and error process, choosing identical values for the % contamination in active and inactive N, and re-calculating X_t/N_0 and α_B. An observed value of α_t = 1600 c./min. still requires about 4–5% contamination. For the seven minute runs, the necessary contamination is somewhat less. (b) Contamination of re-isolated X in the runs of Table III with N clearly cannot be a serious factor, since β_t is much less than β_0 due to exchange. Thus, for run 200, X of α = 640 c./min. would have to be contaminated with thirty times its weight of N of $\beta = 0.54 \times 3017$ in order to have an observed α = 1600 c./min.

[10] From equation 1, $A/(1 - A) = (k_5N - k_6X)/(k_4MC - k_3X)$. This reduces to a constant, $k_6(k_4 + k_5)/(k_1k_4)$, on the assumption of a steady state in C. The observation that the $A/(1 - A)$ ratio appears to change with time presumably signifies that the steady state condition is not satisfied, undoubtedly because of irreversible side reactions. This does not change the conclusions from the isotope results. A referee has pointed out that $A/(1 - A)$ should also be a constant if the reaction $N \rightleftarrows M + C$ approaches equilibrium.

[11] (a) K. Alder and G. Stein, *Angew. Chem.*, **50**, 510 (1937); (b) A. Wassermann, *J. Chem. Soc.*, 828, 1511 (1935); 432 (1936); 612 (1942); *Trans. Faraday Soc.*, **34**, 128 (1938); **35**, 841 (1939); (c) Professor Ronald F. Brown has pointed out the formal possibility that an external mechanism could involve four-center rear-side displacement of M by external M. Our results do not eliminate this possibility.

[12] R. M. Noyes, *J. Chem. Phys.*, **18**, 999 (1950); **22**, 1349 (1954); THIS JOURNAL, **77**, 2042 (1955).

[13] (a) J. Franck and E. Rabinowitch, *Trans. Faraday Soc.*, **30**, 20 (1934); (b) E. Rabinowitch and W. C. Wood, *ibid.*, **32**, 1381 (1936).

[14] Professor Karol J. Mysels has pointed out that the caged aggregate also must represent a potential energy minimum, since it is flanked on one side by an activation energy for escape from the cage and on the other by an activation energy for recombination by covalent bond formation.

erization experiments with optically active adducts in an attempt to find a basis for favoring one description over the other.[15]

Acknowledgment.—We are indebted to the Office of Ordnance Research for financial support, and to Professors S. W. Benson and G. S. Hammond for helpful comments.

LOS ANGELES 7, CALIFORNIA

[15] Diene additions of anthracenes to maleic anhydride involve preliminary (or competing), rapidly reversible complex formation between the addends [L. J. Andrews and R. M. Keefer, THIS JOURNAL, **77**, 6284 (1955)]. It should be pointed out that a maleic anhydride–cyclopentadiene complex that was in such rapid equilibrium with the addends could not account for path A. Thus, in our case, either the M–C complex is protected by a higher barrier for dissociation than are the complexes in the anthracene cases, or else the "cage effect" is the detailed description of path A.

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

The Pinacol Rearrangement of *meso*- and *dl*-3,4-Dimethyl-3,4-hexanediol

BY WILKINS REEVE AND MICHAEL KARICKHOFF

RECEIVED JUNE 25, 1956

The pinacol-pinacolone rearrangement of 3,4-dimethyl-3,4-hexanediol has been studied, and the pinacolone mixture found to consist of 70–73% of the ketone resulting from the migration of an ethyl group, regardless of whether one started with the solid *meso*-pinacol or the liquid *dl*-isomer. The *meso*-form of the pinacol gives a 50% yield of the mixture of ketones whereas the *dl*-rich, liquid mixture, containing some of the *meso*-form, gives only a 17% yield.

Four different investigators[1] have studied the pinacol–pinacolone rearrangement of 3,4-dimethyl-3,4-hexanediol. It was finally demonstrated by Nybergh[1d] that, contrary to the conclusions reached by the three previous investigators, the rearrangement involved the preferential migration of an ethyl group rather than a methyl group.

As the first step in a systematic study of the rearrangement of non-cyclic aliphatic, symmetrical pinacols, we have reinvestigated the rearrangement of this compound and have determined the composition of the mixture of isomeric pinacolones by an analytical method different from that employed by Nybergh. We find that the mixture consists of about 70–73% of the methyl ketone regardless of whether the starting material is the pure solid form of the pinacol, assumed to be the *meso*-form, or the liquid mixture which is rich in the isomeric *dl*-form but contains a presumably small but unknown amount of the *meso*-form. Nybergh estimated the two pinacolones to be formed in the ratio of four of the methyl ketone to one of the ethyl ketone when starting with the solid *meso*-form; he did not examine the liquid form.

We were surprised to find that the yield of the mixture of pinacolones from the *meso*-form of the pinacol was 50% of the theoretical, whereas under the same conditions (pinacol dissolved in an excess of concentrated sulfuric acid at −10° for two hours) the yield of the mixture of pinacolones from the liquid pinacol mixture was only 17%. Inasmuch as an examination of molecular models indicates there should be free rotation between the two central carbon atoms, this result is most interesting. It is reminiscent of the differences Bartlett[2] observed in the rearrangement of *cis*- and *trans*-cyclic pinacols, but is not as pronounced. In the case of the rearrangement of the liquid pinacol mixture, much material is obtained distilling higher than the expected pinacolones. The *meso*-form also gives a high boiling fraction, but in lesser amounts. These high boiling fractions were combined, purified by distillation, and the fraction distilling at 249–254° at 760 mm. found to have a molecular weight and carbon–hydrogen analysis corresponding to a $C_{16}H_{28}$ unsaturated hydrocarbon. It gave the usual qualitative tests for unsaturation.

Our method of analyzing the mixture of pinacolones involved synthesizing reference compounds, *t*-amylethylcarbinol and 3-ethyl-3-methyl-2-pentanol, with which the carbinols obtained from the hydrogenation of the pinacolone mixtures could be compared. *t*-Amylethylcarbinol is the carbinol corresponding to one of the isomeric pinacolones; it was prepared by the Grignard reaction of *t*-amylmagnesium chloride on propionaldehyde. The other carbinol, 3-ethyl-3-methyl-2-pentanol, could not be obtained by a similar Grignard reaction, but was finally prepared by hydrogenating some pure 3-ethyl-3-methyl-2-pentanone. This had been obtained in a crude state from the pinacol rearrangement of 3,4-dimethyl-3,4-hexanediol, purified by repeated recrystallization of the semicarbazone derivative, and finally reconverted to the pure ketone by acid hydrolysis. The two isomeric alcohols were proven to be different by preparing their phthalic acid esters, m.p. 70 and 110°, respectively. The pinacolone mixtures obtained from the rearrangement were purified by steam distillation followed by fractional distillation, and then quantitatively hydrogenated to the mixture of alcohols. The composition of these mixtures was deduced by comparing their infrared absorption spectra with those of the pure isomers.

Experimental

All melting points are corrected. Analyses are by Mrs. Mary Aldridge and Miss Kathryn Gerdeman.

***t*-Amylethylcarbinol.**—*t*-Amylmagnesium chloride in an ether solution, standardized by titrating an aliquot with standard acid, was allowed to react with an equivalent amount of propionaldehyde in a nitrogen atmosphere under the usual Grignard conditions. From 4.5 moles, there was obtained 37 ml., b.p. 67° at 19 mm., $n^{25.5°}D$ 1.4320. The carbon analysis was 0.7% low. The material was purified through the phthalic acid ester prepared by heating 20 g. of the carbinol with 20 g. of phthalic anhydride at 110° for 15

---

[1] (a) G. Lawrinowitsch, *Ann.*, **185**, 123 (1877); (b) P. Herschmann, *Monatsh.*, **14**, 233 (1893); (c) B. Braun and H. Kittel, *Monatsh.*, **27**, 803 (1906); (d) B. Nybergh, *Ber.*, **55B**, 1960 (1922).

[2] (a) P. D. Bartlett and A. Bavley, THIS JOURNAL, **60**, 2416 (1938); (b) P. D. Bartlett and R. F. Brown, *ibid.*, **62**, 2927 (1940).