solvent and diluting to a measured volume in a volumetric flask. The stock solutions were distributed by hypodermic syringe between sample vials which were equipped with 10/30 $\mathfrak{T}$ joints at the neck, and the quantity of sample was determined by weight. The samples were doubly degassed, that is, frozen in a Dry Ice–trichloro-ethylene slurry, degassed, melted, re-frozen, and degassed again. The vials were then sealed while under vacuum.

The runs were carried out in an oil-bath thermostated to the proper temperature ±0.04 degree. The bath temperatures were determined by an NBS standardized 0.1° thermometer.

Iodometric assay methods were used, using acetone as the assay solvent for all runs except for the runs in acetophenone.[19] We found it difficult to obtain reproducible results in the acetophenone runs using the acetone method, but the method using isopropyl alcohol as the solvent for iodometric assay gave good results.[20]

It was determined that double bonds of the type such as are to be expected in the products of the decompositions of γ-benzylidenebutyryl peroxide do not interfere with the iodometric assay. Thus in test experiments it was shown that addition of more than an equivalent of γ-benzylidenebutyric acid to solutions of iodine in isopropyl alcohol and acetone did not alter the observed titer of the iodine solution with standard sodium thiosulfate solution.

The kinetics run on the decomposition of γ-benzylidenebutyryl peroxide in carbon tetrachloride in the presence of products (Table I) was performed as follows: 100 ml. of a stock solution of 0.091 M peroxide in carbon tetrachloride was placed in a flask with a previously constricted neck. The flask was degassed and sealed under vacuum. The flask was then placed on the bath thermostated at 70°, where it remained until the concentration of peroxide was 0.026 M, whereupon the flask was broken, the contents distributed between 9 vials, and a kinetics run performed.

1,1-Diphenyl-2-picrylhydrazyl.—Commercial 1,1-diphenyl-2-picrylhydrazine (5.1 g., 0.013 mole), 5.1 g. of anhydrous sodium sulfate and 31.4 g. (0.13 mole) of lead peroxide were mixed together in 100 ml. of reagent grade benzene. After stirring the mixture for 2 hours at room temperature, the solids were removed from the dense violet colored solution by repeated suction filtration. The solution was evaporated to dryness in a stream of dry nitrogen, and the impure DPPH was recrystallized three times from benzene–petroleum ether mixtures. The lustrous needles which resulted (the 1:1 benzene complex) were then heated *in vacuo* at 80° for 20 hours.[21] The pure DPPH obtained (3.0 g., 0.008 mole) corresponds to a 59% yield, based on the hydrazine; m.p. 134° (reported[22] 137°). *Anal.* Calcd. for $C_{18}H_{12}N_5O_6$: C, 54.8; H, 3.1. Found: C, 54.8; H, 3.3.

Kinetics Run Reported in Table IV.—1,1-Diphenyl-2-picrylhydrazine (20.9 mg.) DPPH was weighed out and dissolved in 100 ml. of carbon tetrachloride solution, designated E-44 1; 10 ml. of E-44 1 was diluted to 50 ml., giving E-44 2, with (DPPH) = 1.06 × 10^{-4} M. The control vial contained E-44 2. E-44 3 was prepared by dissolving 26.4 mg. of γ-benzylidenebutyryl peroxide (98.7% pure by duplicate iodometric assays) in 100 ml. of carbon tetrachloride. E-44 4 (samples I and II) was prepared by mixing 10 ml. of E-44 1 and 5 ml. of E-44 3, and diluting with carbon tetrachloride to 50 ml.

The reagent grade carbon tetrachloride used in this experiment had been previously distilled twice on a 4-ft. glass helices-packed column from (1) phosphorus pentoxide and (2) sufficient DPPH to give the solution a deep purple color.

The sample vials used were constructed of 1 cm. (i.d.) square Pyrex tubing, which was sealed off at the bottom, and connected at the top, *via* a constricted neck, to a short length of regular Pyrex tubing which was terminated by a 10/30 male joint (for attachment to vacuum manifold).[22] square Pyrex tubing, which was wealed off at the bottom. The degassing procedure used was identical to that used in the iodometric runs, except that the vials were wrapped with aluminum foil prior to degassing, and the manifold was flooded with helium twice during the degassing process.

Four vials were used in the experiment: two samples containing E-44 4, one containing E-44 2 (control) and one containing carbon tetrachloride (blank for spectrophotometer as does a regular cuvette.

The run in which propylene carbonate was used as solvent was performed in an analogous way.

---

[19] A. V. Tobolsky and R. B. Mesrobian, "Organic Peroxides," Interscience Publishers, Inc., New York, N. Y., 1954, pp. 52–53.

[20] A. T. Blomquist and A. J. Buselli, *J. Am. Chem. Soc.*, **73**, 3883 (1951), obtained best results when the acetone method of assay was used for kinetics experiments in which benzoyl peroxide was decomposed in acetophenone. The reason for our difficulty is not clear.

[21] J. A. Lyons and W. F. Watson, *J. Polymer Sci.*, **18**, 141 (1955).

[22] The precision bore square tubing was obtained from the Fisher and Porter Co., Warminster, Pa.

[CONTRIBUTION FROM THE SHELL DEVELOPMENT CO., EMERYVILLE, CALIF.]

Catalytic Free Radical Rearrangement of Alkylbenzenes

BY LYNN H. SLAUGH AND JOHN H. RALEY

RECEIVED FEBRUARY 8, 1962

Catalytic free radical rearrangements (*via* 1,2-phenyl shifts) of several alkylbenzenes have been achieved in good yields by heating the latter in the presence of halogen- or sulfur-containing promoters. A free radical chain mechanism is proposed for these reactions depicting the important function of chain transfer agents produced from the promoters.

Introduction

Free radicals capable of undergoing rearrangement, *via* a 1,2-phenyl migration, such as the neophyl radical, have been obtained in high yields only by the decarbonylation of aldehydes[1] and other stoichiometric reactions.[2] Also, these radicals have been prepared in low yields by a free radical-initiated pyrolysis of alkylbenzenes[3] and more recently by the decomposition of peroxides in alkylbenzenes.[4] We have been able to produce these free radicals in high yields from alkylbenzenes by the use of an effective free radical chain transfer agent (TH) in the presence of a free radical initiator (In·)

$$\mathrm{In}\cdot + \mathrm{HT} \rightleftarrows \mathrm{InH} + \mathrm{T}\cdot$$

$$\mathrm{RH} + \mathrm{T}\cdot \rightleftarrows \mathrm{R}\cdot + \mathrm{TH}$$

The incipient phenylalkyl radicals rearrange *via* a 1,2-phenyl migration. Consequently, free radical-catalyzed isomerizations of alkylbenzenes have been obtained.[5]

---

[1] S. Winstein and F. H. Seubold, *J. Am. Chem. Soc.*, **69**, 2916 (1947); D. Y. Curtin and M. J. Hurwitz, *ibid.*, **74**, 5381 (1952); F. H. Seubold, *ibid.*, **75**, 2532 (1953); L. H. Slaugh, *ibid.*, **81**, 2262 (1959).

[2] W. H. Urry and M. S. Kharasch, *ibid.*, **66**, 1438 (1944); W. H. Urry and N. Nicolaides, *ibid.*, **74**, 5163 (1952); C. G. Overberger and H. Gainer, *ibid.*, **80**, 4561 (1958).

[3] H. Pines and C. N. Pillai, *ibid.*, **81**, 3629 (1959), and references cited therein.

[4] H. Pines and C. N. Pillai, *ibid.*, **82**, 2921 (1960).

[5] For a preliminary report of the work see L. H. Slaugh and J. H. Raley, *ibid.*, **82**, 1259 (1960).

TABLE I

FREE RADICAL-CATALYZED ISOMERIZATION OF ALKYLAROMATICS: AUTOCLAVE EXPERIMENTS[e]

Promoter, I_2 (1.0 mole %)

Alkylbenzene isomerized	Expt.	Temp., °C.	Pressure,[a] p.s.i.	Time, hr.[b]	Conversion, %	Selectivity	Isomer pair distribution[d] moles/100 moles of alkylbenzene introduced[c] More branched	Less branched
Cumene	2	450	750	1.0	71.9	60.7	28.1	43.7
sec-Butylbenzene	3	400	500	3.0	33.7	38.1	66.3	12.8
tert-Butylbenzene	4	400	500	3.0	73.4	84.4	26.6	62.0
n-Propylbenzene	8	450–470	1000	1.0	72.5	15.2	10.7	27.5
p-Cymene	10	450	800	1.0	78.6	41.0	21.4	32.3
α-Methylstyrene	21	450	1100	1.0	Polymer			0.0
Isobutylbenzene	25	450	600	1.0	84.5	6.1	5.2	15.5
Cumene	47	450	680	1.0	61.2	70.0	38.8	42.8

[a] Maximum pressure attained; initial pressure at room temperature was atmospheric. [b] Approximately 1 hour was required to heat the autoclave to the desired temperature; the cooling period was 1 to 3 hours. [c] Calculated on a no-loss basis. [d] Refers to the isomer pairs pertinent to the indicated reactant hydrocarbon: cumene/*n*-propylbenzene; *tert*-butylbenzene/isobutylbenzene; *sec*-butylbenzene/*n*-butylbenzene; *p*-cymene/1-methyl-4-*n*-propylbenzene; α-methylstyrene/β-methylstyrene. [e] Material balance, 98–100% except expt. 21 (85%).

TABLE II

FREE RADICAL-CATALYZED ISOMERIZATION OF CUMENE: AUTOCLAVE EXPERIMENTS

Expt.	Promoter, mole, %	Temp.,[a] °C.	Pressure,[b] p.s.i.	Time,[c] hr.	Conversion, %	Selectivity	Isomer pair distribution moles/100 moles of cumene introduced[d] Cumene	*n*-Propylbenzene	Material balance, %
2	I_2, 1	450	750	1.0	71.9	60.7	28.1	43.7	100
13	Br_2, 1	300	110	1.0	~0	..	100	0	100
16	Br_2, 1	450	600	1.0	53.3	80.4	46.7	42.9	100
17[e]	C_6H_5SH, 2	450	..	1.0	<1	<1%	>99	..	100
23[e]	$(C_6H_5S)_2$, 1	500	..	1.0	61.5	54.3	38.5	33.4	91
24	$(C_6H_5S)_2$, 1 U.v.-light	150	15	6.0	0	0	100	0	100
27	C_6H_5I, 1	450	1100	1.0	80.6	35.0	19.4	27.9	96
47[e]	I_2, 1	450	680	1.0	61.2	70	38.8	42.8	99
64[e]	$CH_3CHClCH_3$, 2	450	750	1.0	13.5	95.1	86.5	12.9	96
79	Amorphous Sulfur, 4	450	800	1.0	36.3	75.0	63.7	27.2	92
83	H_2S, 4	450	800	1.0	54.5	62.4	45.5	34.1	95

[a] Temperature maintained during the designated residence time. [b] Maximum pressure attained; at room temperature the initial pressure was atmospheric. [c] Approximately 1 hour was required to heat the autoclave to the desired temperature; the cooling of the vessel required from 1 to 3 hours. [d] Calculated on a no-loss basis. [e] Sealed glass tube experiments.

Results and Discussion

Many of the isomerization reactions were studied by heating the alkylbenzenes and promoters (1–10% mole) in an autoclave at 300–500° for one to three hours. In certain instances, the reactants were sealed in a Pyrex tube for protection against the metal walls of the autoclave. The results of these experiments are listed in Tables I and II. While interpreting these data, it must be borne in mind that the time required for heating and cooling of the autoclave varied from experiment to experiment. Consequently, only gross comparisons of experimental data should be made.

To obtain a more quantitative comparison of the reaction variables, the isomerization of cumene was studied further using a metallic tubular flow reactor (450–525°, 500–1500 p.s.i.). The reactants were introduced into the reactor from a pressurized bomb at such a rate as to maintain the desired residence time. This technique permits isothermal operation at controlled pressures and residence times. Some of the reactions were carried out in the presence of oxygen. For these, a mixture of oxygen in helium or argon was metered into the reactor at the desired rate. The results of the flow experiments are listed in Table III.

The main side products of the above reactions were lower molecular weight alkylbenzenes and C_1–C_5-hydrocarbons resulting from cleavage reactions (see Experimental). The amount of coke formation was always small. Very little (< 0.4%) disproportionation to dialkylbenzenes occurred.

Alkylbenzenes Isomerized.—Cumene, *tert*-butylbenzene, *sec*-butylbenzene and *p*-cymene have been isomerized to *n*-propylbenzene, isobutylbenzene, *n*-butylbenzene and 1-methyl-4-*n*-propylbenzene, respectively (see Table I). The reverse transformations of *n*-propylbenzene to cumene and isobutylbenzene to *tert*-butylbenzene have also been obtained, thus demonstrating the reversibility of these reactions.

The following autoclave experiments are singled out to illustrate the yields for the isomerization reactions. Selectivities (conversion × selectivity/100 = yield) to *n*-propylbenzene as high as 60.7% (expt. 2) and 70.0% (expt. 47) were obtained with corresponding cumene conversions of 71.9% and 61.2%. Also, a selectivity for isobutylbenzene of

TABLE III

FREE RADICAL-CATALYZED ISOMERIZATION OF CUMENE: FLOW EXPERIMENTS

Temperature, 500°; pressure, 500 p.s.i.

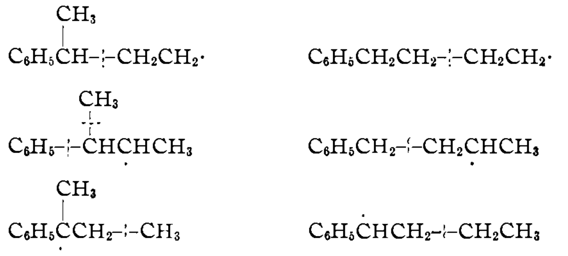
Expt.	Promoter, mole %	Res. time, min.	Conversion, %	Selectivity	Moles/100 moles cumene introduced[a] Cumene	n-Propylbenzene	Material balance, %
30	I_2, 1.0	8.7	23.7	84.8	76.3	20.1	>90
32	$C_6H_5CH_2Br$, 2.0	10.5	41.3	81.0	58.7	33.5	94.1
41	CH_3CHICH_3, 2.0	~11.0	38.9	72.6	61.1	28.2	97.6
56	$C_6H_5CH_2Br$, 2.0	6.0	36.8	84.6	63.2	31.1	95.1
62	$CH_3CHClCH_3$, 2.0	10.4	4.7	..	95.3	2.4	98.3
72	$(C_6H_5S)_2$, 1.0	5.0	1.8	..	98.2	1.2	100
73	$(C_6H_5S)_2$, 5.0	5.0	20.2	64.0	79.8	12.9	99.7
75	C_6H_5SH, 2.0 O_2, 0.5	10.0	<5.0	..	..	2.8	100
76	C_6H_5SH, 10.0 O_2, 2.5	11.1	19.3	63.1	80.7	12.2	99.5
77	$(C_6H_5S)_2$, 5.0	10.3	33.1	70.5	66.9	23.3	100
81[b]	CH_3CH_2SH, 5.0 O_2, 1.25	10.0	36.6	49.6	63.4	18.1	96.6
92	C_6H_5SH, 10.0	10.0	15.2	68.4	84.8	10.4	95.5

[a] No-loss basis; all values have been corrected for impurities resulting from the promoter. [b] 525°.

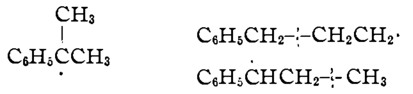
84.4% (expt. 4) was obtained at a 73.4% conversion of *tert*-butylbenzene.

The selectivity (38.1%) for the conversion (33.7%) of *sec*-butylbenzene to *n*-butylbenzene (expt. 3) is lower. This is attributed to the greater number of hydrogen atoms in *sec*-butylbenzene and its rearranged product, *n*-butylbenzene, relative to cumene and its rearranged product, *n*-propylbenzene, which upon abstraction, produce phenylalkyl radicals incapable of rearranging but prone to undergo a carbon–carbon bond cleavage, *e.g.*

sec-Butylbenzene and product



Cumene and product



Because of the reversibility of these reactions, one might anticipate the composition of the final product to be an equilibrium mixture of the two isomeric alkylbenzenes concerned. In the case of propylbenzenes, the calculated equilibrium mixture[6] is ~31% cumene and 69% *n*-propylbenzene at 427°. However, the ratio of *n*-propylbenzene to cumene in the product is always less than the equilibrium value. This indicates that the rate of *n*-propylbenzene formation becomes slower than its rate of cracking as the cumene concentration decreases and the *n*-propylbenzene concentration increases.

The low selectivity of the reverse step, that is, isomerization of either *n*-propylbenzene (expt. 8) or isobutylbenzene (expt. 25) suggests a continuously decreasing selectivity for the forward reaction as conversion is increased. This appears to be the case (*e.g.*, compare expt. 2 and 47).

The isomerization of *p*-cymene produces 1-methyl-4-*n*-propylbenzene (expt. 10). The absence of *m*-cymene, *o*-cymene and 1-methyl-3-*n*-propylbenzene in the product, as determined by infrared and gas-chromatographic analyses, demonstrates that the isomerization of the side chain occurs without a change of position on the benzene ring.

An attempt to isomerize α-methylstyrene (expt. 21) to β-methylstyrene was unsuccessful. Considerable polymer formation occurred. There was a small amount of *n*-propylbenzene produced which may have arisen from cumene formed during the reaction.

Isomerization Promoters.—Pines and Pillai first attempted to promote the free radical isomerization of alkylbenzenes.[3] They reported that the addition of a small amount of bibenzyl, a free radical source at high temperature, increases the extent of isomerization of cumene to *n*-propylbenzene at 450° and 410 atm. from 0.7 to 1.4%, thus suggesting the free radical character of this and other similar rearrangements observed previously during the pyrolysis of alkylaromatics.[7] Pines and Pillai[4] have also demonstrated that partial isomerization can be obtained by decomposing peroxides in alkylbenzenes even at temperatures < 140°. In each instance, the yield of rearranged product was low because of a rather short free radical chain. That is, the radicals generated from the promoters abstracted hydrogen atoms from the side chain of the

---

(6) F. D. Rossini, API Project 44, Carnegie Institute, Pittsburgh, Penna., 1955, "Selected Values of Thermodynamic Functions."

(7) V. N. Ipatieff, B. Kvetinskas, E. E. Meisinger and H. Pines, *J. Am. Chem. Soc.*, **75**, 3323 (1953).

alkylbenzenes to give radicals which either rearranged, *via* a 1,2-phenyl shift, coupled, disproportionated or cleaved. Rather than propagating the chain by abstracting a hydrogen atom from an unrearranged alkylbenzene, the rearranged radicals preferred to undergo the above chain-terminating reactions.

Elemental sulfur, hydrogen sulfide, iodine and several organic iodides, bromides, chlorides, mercaptans and disulfide have been found to be more effective promoters for the isomerization reactions (Tables II and III). A promoter concentration as low as one mole % is sufficient in most cases to attain substantial isomerization. The above promoters are particularly effective because they not only yield chain-initiating free radicals, such as, Br·, I·, RS·, R·, S_x·, etc.,[8] but also pyrolyze to give chain transfer agents, such as HI, HBr, RSH, etc., which are capable of propagating a chain reaction by reacting with the rearranged radicals (see proposed mechanism below). Chain transfer agents also may be formed by the reaction of the initiator free radicals with the alkylbenzene or they may be introduced directly as in the case of mercaptans and H_2S. Apparently the bromine-containing promoters are effective only at temperatures above 300° since isomerization did not occur at this temperature but proceeded readily at 450° (Table II). At higher temperatures, say 525°, cleavage reactions became quite severe. An attempt to use phenyl disulfide in the presence of ultraviolet light at 150° (expt. 24) was not successful.

Metal surfaces are not necessary for the promoters to be effective since isomerization reactions occur just as readily in Pyrex tubes (Tables II and III).

It is clear from the data in Table III that benzyl bromide is a more active promoter than iodine or isopropyl iodide. During a 6.0-minute residence time, benzyl bromide promoted a conversion of cumene equal to or greater than those produced by isopropyl iodide or iodine in 8.7 and 11.0 minutes, respectively, other conditions being equal. On the other hand, isopropyl chloride gave a much lower conversion, *i.e.*, 4.7%, compared to 41.3% for benzyl bromide under comparable conditions. Mercaptans and disulfides are less active than iodides or bromides. In general, a much higher concentration of the sulfur-containing promoters is required. An effort was made to increase the effectiveness of thiophenol as a promoter by the addition of oxygen. However, the mixture (expt. 76) was scarcely better than thiophenol alone (expt. 92).

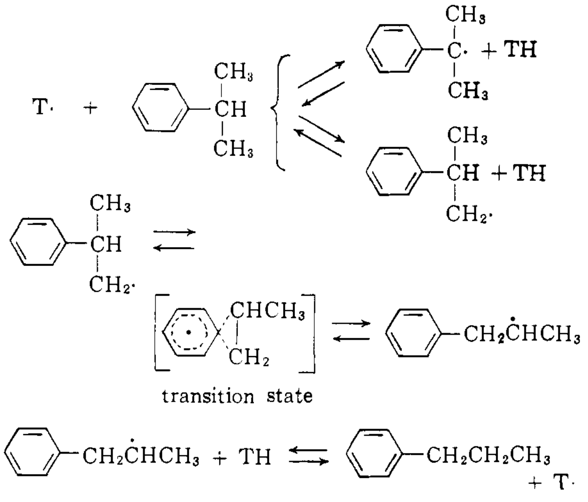
Mechanism.—The following mechanism depicting the important function of the chain transfer agent is proposed for the free radical-catalyzed isomerization of alkylbenzene. The isomerization of cumene to *n*-propylbenzene is used as an example

$$\text{alkylbenzene or promoter} \xrightarrow{\Delta} \text{In}\cdot \text{ (initiator radical)}$$

$$\text{promoter} \xrightarrow{\Delta} \text{T}\cdot \text{ or TH (hydrogen transfer agent)}$$

$$\text{T}\cdot + \text{hydrogen donor} \longrightarrow \text{TH}$$

$$\text{In}\cdot + \text{TH} \longrightarrow \text{InH} + \text{T}\cdot$$



The proposed free radical mechanism is supported by several lines of evidence: (1) substances which upon pyrolysis are known to produce free radicals,[9] either directly or as a result of chain transfer reactions, promote the isomerization. In the absence of a promoter < 1% isomerization occurs under these conditions.

(2) A carbonium ion mechanism is unlikely because products arising from methyl migration processes[15,16] were not formed. Thus, *n-butylbenzene* and not *isobutylbenzene* was obtained upon isomerization of *sec*-butylbenzene with the promoters as noted above. However, isobutylbenzene is the product obtained upon treatment of *sec*-butylbenzene with water-activated aluminum chloride.[15] Furthermore, disproportionation reactions to benzene and polyalkylbenzenes[17] were absent in the present isomerizations.

(3) As anticipated for a free radical mechanism, metal surfaces were found to be unnecessary since the reactions readily occur in Pyrex tubes as well as in metal autoclaves.

(4) Diphenyl disulfide, which probably produces thiyl radicals more readily upon heating than does thiophenol, was found to be a better isomerization promoter than the latter (Table III).

(5) Hydrogen bromide[18] and mercaptans[19] are

---

[8] Some initiating free radicals also may result from the pyrolysis of the alkylbenzene.

[9] Iodine,[10] alkyl iodides,[11] alkyl bromides,[11] disulfides,[12] sulfur,[13] mercaptans,[14] and, with less certainty, alkyl chlorides.[11]

[10] G. Stark and M. Bodenstein, *Z. Elektrochem.*, **16**, 961 (1910); H. Braune and H. Ramstetter, *Z. physik. Chem.*, **102**, 480 (1922); T. DeVries and W. H. Rodebush, *J. Am. Chem. Soc.*, **49**, 656 (1927).

[11] E. W. R. Steacie, "Atomic and Free Radical Reactions," Vol. I, 2nd ed., Reinhold Publishing Corp., New York, N. Y., 1954, pp. 253–263.

[12] A. Schönberg and A. Mustafa, *J. Chem. Soc.*, 889 (1949).

[13] D. M. Gardner and G. K. Fraenkel, *J. Am. Chem. Soc.*, **78**, 3279 (1956).

[14] A. H. Sehon and B. deB. Darwent, *ibid.*, **76**, 4806 (1954).

[15] C. D. Nenitzescu, I. Mecsoiu, A. Glatz and M. Zalman, *Ber.*, **92**, 10 (1959).

[16] R. M. Roberts, Y. W. Han, C. H. Schmid and D. A. Davis, *J. Am. Chem. Soc.*, **81**, 640 (1959).

[17] R. Heise, *Ber.*, **24**, 768 (1891); D. A. McCaulay and A. P. Lien, *J. Am. Chem. Soc.*, **75**, 2411 (1953); D. A. McCaulay, M. C. Hoff, N. Stein, A. S. Couper and A. P. Lien, *ibid.*, **79**, 5808 (1957); D. A. McCaulay and A. P. Lien, *ibid.*, **79**, 5953 (1957).

[18] J. A. Ridgway, Jr., *Ind. Eng. Chem.*, **50**, 1531 (1958); G. B. Kistiakowsky and E. R. Van Artsdalen, *J. Chem. Phys.*, **12**, 469 (1944); K. B. Wiberg and L. H. Slaugh, *J. Am. Chem. Soc.*, **80**, 3033 (1958).

noted chain transfer agents and even the relatively strong H–Cl bond in hydrogen chloride is susceptible to free radical attack.[20]

(6) The isomerization of *p*-cymene (1-methyl-4-isopropylbenzene) exclusively to 1-methyl-4-*n*-propylbenzene is consistent with known free radical rearrangements[21] in that the relative positions of the two ring substituents are unchanged during the isomerization.

Experimental

Autoclave Experiments.—One to 10 mole % of an isomerization promoter (organic halides, mercaptans, etc.) and 0.1–0.5 mole of an alkylbenzene were placed in a 250-cc. autoclave.[22] After being sealed and flushed with nitrogen, the autoclave was rocked and heated at the desired temperature (300–525°) for 1 to 3 hours. The gaseous product was vented from the cooled vessel into a brine-displacement gas holder. The liquid product was washed with 20% sodium hydroxide solution, followed by water and dried over calcium chloride.

When reactions were carried out in sealed glass tubes, a calculated amount of the alkylbenzene was placed in the autoclave with the sealed tube. This procedure equalized the pressures inside and outside of the sealed tube, thereby preventing bursting of the latter at the elevated temperatures.

Flow Experiments.—The alkylbenzene and promoter were placed in a pressure-tight, stainless steel reservoir vessel mounted on a Metrogram balance. The reactants were forced, at a desired rate controlled by a needle valve, through a nitrogen-flushed line into a vertical reaction tube[22] (approximately 0.75 × 36 inches) held in an electrically heated furnace. This was accomplished by maintaining a nitrogen pressure inside the stainless steel reservoir vessel 100–250 p.s.i. greater than that in the reaction tube. The desired pressure in the reaction vessel (500–1500 p.s.i.) was maintained by a Grove regulator below the furnace. The residence times for the reactants in the vertical reactor were calculated without correction for non-ideality from the rates of decrease in weight of the reservoir vessel as measured by the Metrogram balance.

When desired, oxygen or inert gases were metered into the vertical reactor through a second line.

The liquid product was collected in an ice trap at the bottom of the vertical reactor and the gaseous product in a brine-displacement gas holder. The liquid product was washed and dried as above.

Product Analyses.—The gaseous and liquid products were analyzed both mass spectrometrically and by gas–liquid chromatographic techniques (g.l.c.) using a column packed with 30–40 mesh, silicone (DC-710)-impregnated firebrick. Compounds corresponding to the g.l.c. peaks were trapped and identified mass spectrometrically.

tert-Butylbenzene and isobutylbenzene in the products were determined by infrared analyzes. For this purpose, peaks at 13.10 and 13.55μ, respectively, were used. Infrared analysis was also employed for the detection of *o*-cymene, *m*-cymene and 1-methyl-3-*n*-propylbenzene resulting from the isomerization of *p*-cymene. These compounds apparently were not formed from *p*-cymene.

The following autoclave experiment is given as a typical example for the isomerization of cumene. At 450° and 750 p.s.i., using one mole % iodine promoter, 72% of the cumene was converted in 60 minutes. From 1.0 mole of cumene introduced, the following moles of hydrocarbons were recovered: CH_4, 0.067; C_2H_6, 0.043; C_3H_8, 0.014; C_4H_{10}, 0.006; $C_4H_8 + C_5H_{10}$, 0.0006; benzene, 0.040; toluene, 0.095; ethylbenzene, 0.143; unreacted cumene, 0.278; *n*-propylbenzene, 0.432; C_{10}–C_{18}, 0.001; solids (coke), 0.018.

Alkylbenzenes and Promoters.—The cumene, *tert*-butylbenzene, *sec*-butylbenzene, *n*-butylbenzene and *p*-cymene were of the highest purity available and were found by g.l.c. and infrared analyses to be essentially free of impurities. Whenever an impurity was detected, it was removed by efficient distillation of the alkylbenzene. The promoters were reagent grade materials and were further purified, where possible, by careful distillation.

Acknowledgments.—We wish to express our appreciation to P. A. Wadsworth and J. M. Gordon for mass spectrometric and infrared analyses and to L. F. Focha and G. W. Schoenthal for assistance in carrying out the autoclave and flow experiments.

---

(19) C. Walling, *J. Am. Chem. Soc.*, **70**, 2561 (1948); R. A. Gregg, D. M. Alderman and F. R. Mayo, *ibid.*, **70**, 3740 (1948).

(20) J. H. Raley, F. F. Rust and W. E. Vaughan, *ibid.*, **70**, 2767 (1948).

(21) W. H. Urry and N. Nicolaides, *ibid.*, **74**, 5163 (1952).

(22) Stainless steel and Hastelloy C reaction vessels were used with sulfur- and halogen-containing promoters, respectively.

COMMUNICATIONS TO THE EDITOR

THE USE OF UREA TO ELIMINATE THE SECONDARY BINDING FORCES IN ION EXCHANGE CHROMATOGRAPHY OF POLYNUCLEOTIDES

Sir:

The separation of organic compounds by ion exchange chromatography is a complex process which is controlled, in part, by ionic interactions and by secondary binding forces. In the separation of proteins, these secondary forces are known to include hydrogen bonding and lipophilic interaction.[1] The latter force also has been shown to affect the separation of small molecules such as nucleotides and polynucleotides[2] and it now appears that hydrogen bonding could also be of importance. For example, studies on the chromatographic separation of thymidylic acid homopolymers[3] showed that polystyrene anion exchange resins strongly held all polymers larger than the dinucleotide, presumably because of the lipophilic interaction between the thymidine and polystyrene systems. This type of binding was circumvented by using a cellulose anion exchanger (DEAE-cellulose[4]) and a good separation of thymidylic acid polymers was thus achieved. However, attempts to separate mixed polynucleotides resulting from the enzymic degradation of deoxyribonucleic acids (DNA) (see Fig. 1A) and ribonucleic acids (RNA)[5] using the same technique

---

(1) S. Moore and W. H. Stein, "Advances in Protein Chemistry," Vol. XI, Academic Press, Inc., New York, N. Y., 1956, p. 217.

(2) W. E. Cohn in E. Heftman, "Chromatography," Reinhold Publishing Corp., New York, N. Y., 1961, p. 554.

(3) G. M. Tener, H. G. Khorana, R. Markham and E. H. Pol. *J. Am. Chem. Soc.*, **80**, 6223 (1958).

(4) E. A. Peterson and H. A. Sober, *ibid.*, **78**, 751 (1956).