TABLE IV

DERIVATIVES OF AMINO ALCOHOLS

Compound	M.p., °C.	Carbon, % Calcd.	Carbon, % Found	Hydrogen, % Calcd.	Hydrogen, % Found	Nitrogen, % Calcd.	Nitrogen, % Found
5 oxalate	181–181.5	55.15	54.98	9.26	9.20	8.04	8.13
9 hydrogen oxalate	104–105	51.49	51.72	8.21	8.13	6.00	5.77
9 bisbenzoate	118–119						
30 picrate	154–155	51.57	51.86	6.83	6.59	12.67	12.63
14 picrate	196–197	55.45	55.74	5.93	6.05	11.76	11.80
31 hydroiodide	203–204	44.36	43.91	8.01	8.02	4.26	4.43
34 bisbenzoate	94.5–95	75.18	75.11	7.17	7.39	3.99	3.88
35 bisbenzoate	117–117.5	75.58	75.23	7.45	7.64	3.83	3.66

filtered and the excess zinc was washed with 5% hydrochloric acid. Basification, followed by continuous extraction with methylene chloride, gave 354 mg. of crude product. Chromatography over a small quantity of alumina and elution with ether gave 277 mg. (56%) of the amino alcohol **31**, m.p. 104–104.5°.

Catalytic Hydrogenation. A. Palladium-on-Carbon. Reduction of 12b to 31.—A solution of 500 mg. of **12b** in 15 ml. of ethanol was added to 200 mg. of prereduced 10% palladium–carbon catalyst in 10 ml. of ethanol; 90% of the theoretical amount of hydrogen was taken up in 45 min. After filtration and evaporation of the solvent, 440 mg. of crude product was obtained. Chromatography on alumina gave 415 mg. (81.5%) of **31**, m.p. 104–104.5°.

N-Phenyl-*trans*,*trans*-2-(2′-hydroxy-2′-propyl)-5-methylcyclohexylamine (14).—Hydrogenation of 1.4 g. (0.006 mole) of **12f** in the presence of 0.33 g. of 10% palladium–carbon catalyst gave 1.37 g. (97%) of a solid amino alcohol **14**, m.p. 121–123°. Recrystallization from hexane raised the melting point to 129–130°.

Catalytic Reduction. B. Platinum Oxide. Reduction of 12b to 31.—A solution of 500 mg. of isoxazolidine in 25 ml. of ethanol was hydrogenated in the presence of 250 mg. of prereduced platinum oxide. After 18 hr., an additional 195 mg. of catalyst was added. The total uptake of hydrogen amounted to 66%. The crude product was chromatographed to give a 59% yield of amino alcohol **31**, m.p. 104–104.5°.

N-Ethyl,N-methyl-*trans*,*trans*-2-(2′-hydroxy-2′-propyl)-5-methylcyclohexylamine.—The methiodide of **12c** (6.13 g., 0.19 mole) was hydrogenated in 200 ml. of ethanol with prereduced platinum oxide as the catalyst. Evaporation of the solvent gave a crystalline hydroiodide of the amino alcohol, m.p. 203–204°. The salt was dissolved in water, basified, and extracted with methylene chloride. Distillation gave a liquid amino alcohol **32**, b.p. 88–90° (2 mm.), $n^{22}D$ 1.4669.

Lithium Aluminum Hydride Reduction of 12b.—A mixture of 1 g. of **12b**, 0.2 g. of lithium aluminum hydride, and 50 ml. of tetrahydrofuran was heated at reflux for 20 hr. Work up was effected by the addition of 0.2 g. water, 0.6 g. of 15% potassium hydroxide solution, and 0.2 g. of water. After removal of the salts by filtration, the filtrate and washings were dried and concentrated to give 0.86 g. of crude material. Chromatography on alumina gave 0.56 g. of recovered starting material (54.5%) and 0.46 g. (45.5%) of amino alcohol **31**, m.p. 104–104.5°

The amino alcohol products and derivatives are given in Tables III and IV.

N,N-Dimethyl-*trans*,*trans*-2-(2′-propenyl)-5-methylcyclohexylamine (17).—A mixture of 5.97 g. (0.025 mole) of amino alcohol **31** and 10 ml. of acetic anhydride was heated at reflux for 10 hr. The solution was chilled and was basified with 20% potassium hydroxide solution. After extraction with ether, the extract was dried and concentrated. Distillation gave 4.23 g. (75%) of **17**, b.p. 69–70° (3.5 mm.), $n^{25}D$ 1.4658, $[\alpha]^{25}D$ +9.15°.

Anal. Calcd. for $C_{12}H_{23}N$: C, 79.48; H, 12.76; N, 7.73. Found: C, 79.52; H, 13.01; N, 7.29.

The n.m.r. spectrum and infrared spectrum of **17** confirmed the presence of the terminal methylene group.

The picrate was prepared and was recrystallized from 95% ethanol; m.p. 153.5–154°.

Anal. Calcd. for $C_{18}H_{26}N_4O_7$: C, 52.68; H, 6.39; N, 13.65. Found: C, 52.77; H, 6.33; N, 13.94.

N,N-Dimethyl-1-methylamine (18).—The amine **17** was hydrogenated in methanol solution in the presence of 10% prereduced Pd–C catalyst. Upon distillation, there was obtained 0.69 g. (69%) of **18**, b.p. 75–76° (4.9 mm.), $n^{25}D$ 1.4565, $[\alpha]^{25}D$ −49.6° (lit.[38] b.p. 85° at 7 mm., $n^{25}D$ 1.4552, $[\alpha]^{25}D$ −51.20°).

Trimethyl-1-methylammonium Iodide.—The methiodide of **18** was prepared and was recrystallized from acetone; m.p. 192.5–193.5, $[\alpha]^{25}D$ (H_2O, 1.55) −18.7° (lit.[38] m.p. 192.3–192.5°, 193–194°, $[\alpha]^{25}D$ −40.5°, −37.6°), m.m.p. 193–194°.

N,N-Dimethyl-*l*-menthylammonium Picrate.—The picrate of **18** was prepared; m.p. 128.5–129°. The picrate of synthetic N,N-dimethyl-*l*-menthylamine[38] ($[\alpha]^{20}D$ −47.6°) melted at 127.5–128°, m.m.p. 127.5–128°.

Relative Configurations of Isoxazolidines 11c and 11e.—Samples of 131 mg. each of isomeric isoxazolidines **11c** and **11e** were hydrogenated with 10% Pd–C in absolute ethanol to the corresponding amino alcohols (infrared spectra different). Each amino alcohol was acetylated to the diacetyl derivative (infrared spectra different). The diacetates were saponified with 1 *N* sodium hydroxide at room temperature and the N-acetylamino alcohols were isolated (infrared spectra different). Oxidation with potassium dichromate and sulfuric acid in a two-phase system with ether gave N-methyl-N-acetyl-*cis*-2-acetylcyclopentylamine (**15**) (infrared spectra nearly identical). The 2,4-dinitrophenylhydrazones were prepared and were recrystallized from benzene; m.p. 189–190° (from **11c**), 189–190° (from **11e**), m.m.p. 190°.

Acknowledgment.—This work has been supported by a generous grant from the National Science Foundation, and, in part, by the Research Corporation.

(38) N. L. McNiven and J. Reed, *J. Chem. Soc.*, 153 (1952); A. C. Cope and E. M. Acton, *J. Am. Chem. Soc.*, **80**, 357 (1958).

[CONTRIBUTION NO. 1619 FROM THE DEPARTMENT OF CHEMISTRY OF THE UNIVERSITY OF CALIFORNIA AT LOS ANGELES, LOS ANGELES, CALIF.]

Phenonium Ions as Discrete Intermediates in Certain Wagner–Meerwein Rearrangements

BY DONALD J. CRAM

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The case is stated for the existence of phenonium ions in certain Wagner–Meerwein rearrangements.

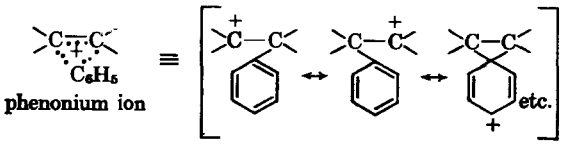
Thirteen years after the original evidence for the existence of ethylene phenonium ions was published,[1] H. C. Brown has in print[2] questioned the validity of the original interpretations.[3] This event requires a summation of the case for the existence of ethylene pheno-

(1) (a) D. J. Cram, *J. Am. Chem. Soc.*, **71**, 3863 (1949); (b) **71**, 3875 (1949).

(2) H. C. Brown, "The Transition State," Special Publication No. 16, The Chemical Society, London, 1962, p. 140.

(3) In numerous seminars, colloquia, and symposia since 1958, H. C. Brown has enthusiastically attacked bridged phenonium ion interpretations

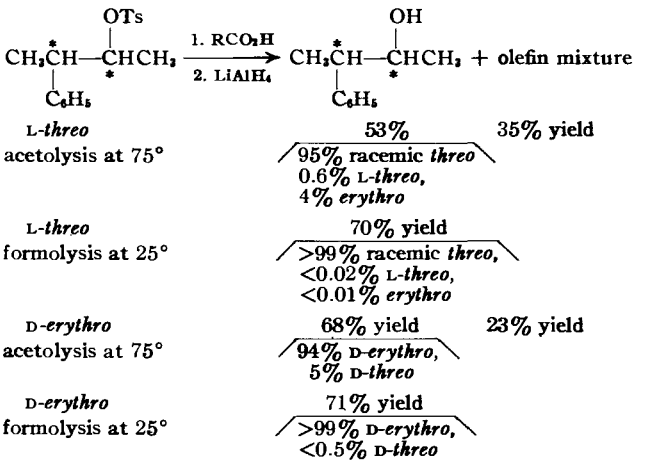
nium ions[4] as an important and discrete class of reaction intermediate, and this article states that case. Occasionally, the facts and interpretations presented touch on Brown's paper, but in general that evidence is selected which must be faced in any serious challenge of these bridged cations as an important part of general carbonium ion theory.

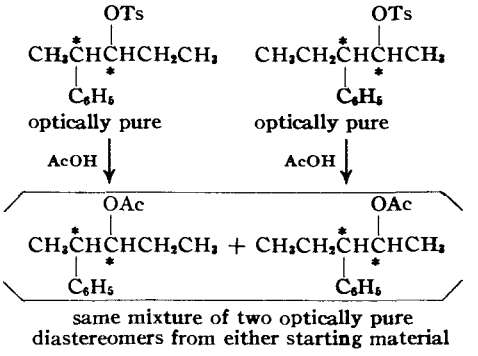


Experimentally, two techniques have been applied to the study of bridged phenyl chemistry: kinetics, and the relationship between the symmetry properties of starting materials and products. Kinetic measurements have provided evidence for neighboring group participation in carbonium ion formation, but *taken alone* do not differentiate between bridged ions and bridged transition states. Rate comparisons reflect only differences in activation free energies, and therefore provide no information about structure after the rate-determining transition state is reached. Study of the stereochemical course of 1,2-rearrangements provides direct evidence for the existence of bridged carbocyclic cations as discrete reaction intermediates. Combination of the two techniques, particularly in systems with the appropriate symmetry properties, provides powerful and convincing evidence for the existence of bridged ions.

Stereochemical Evidence for Phenonium Ions.—The best evidence for a phenonium ion as a discrete intermediate (as distinct from a transition state) is found in the results of solvolyses of the optically pure diastereomers of 3-phenyl-2-butyl *p*-toluenesulfonate (tosylate).[1a,5] Both acetolysis and formolysis were conducted on optically pure tosylates, the ester products were converted to alcohols, and the alcohols and olefins were separated and analyzed.[5] The results are tabulated.[6]

Confirmation that skeletal rearrangements actually occurred in both diastereomeric series was gained when appropriate pairs of stereoisomeric tosylates of 2-phenyl-3-pentanol and 3-phenyl-2-pentanol were found to produce the same mixture of two compounds, one with phenyl attached to C-2 and the other with phenyl on C-3.[1b,7] The stereochemical structures of the pair of products in each experiment were those predicted by analogy with the behavior of the 3-phenyl-2-butyl system.





Any explanation of these results must in detail account for the following facts. (1) A 1,2-phenyl migration occurs in these reactions, but only to the extent of 50% in the butyl system.[8] From either pentyl system, phenyl migrates enough to give about 57% of 3-phenylpentyl and 43% of 2-phenylpentyl product. (2) For that fraction of product which does not rearrange, substitution occurs with very high retention (about 95% in acetolysis[9] and >99.7% in formolysis). (3) For that part which does rearrange, inversion occurs at both the migration origin and terminus with high stereospecificity (about 95% in acetolysis[9] and >99.7% in formolysis).

To account for the stereochemical results with open carbonium ion theory (see Chart I), the following assumptions would have to apply equally well to *all isomers* of the three series. (1) Two open carbonium ions (one unrearranged and one rearranged) would have to equilibrate faster than either would be consumed by solvent. For the *threo*-3-phenyl-2-butyl system in acetic acid, a rate factor of greater than 100 would be required, and in formic acid, a factor of greater than 3000. (2) For that material which does not rearrange, substitution through open carbonium ions would have to occur with very high over-all retention. In the

(4) The earliest suggestion of which the author is aware that bridged aryl systems intervene in 1,2-aryl migrations was made by K. Freudenberg in a paper entitled, "Intramolekulare Umlagerung optisch-activer Systeme" (Sitzungsberichte der Heidelberger Akademie der Wissenschaften, June 19, 1927).

(5) D. J. Cram, *J. Am. Chem. Soc.*, **74**, 2129, 2137 (1952).

(6) The raw product data are not corrected for the fact that in acetic acid, L-*threo*-3-phenyl-2-butyl tosylate gives racemic material (tosylate and acetate) five times as fast as it solvolyzed (ref. 5). In other words, 80% of the final acetate produced came from racemized tosylate, and 20% from optically pure tosylate. Any leakage of *threo*- to *erythro*-tosylate associated with the tosylate racemization would ultimately be reflected in production of *erythro* acetate. An accurate account of the over-all degree of stereochemical control exercised at C-2 and C-3 during the over-all process of converting L-*threo*-tosylate to acetate involves multiplying the stereospecificity rate factors by 4. Such a procedure involves the reasonable assumption that tosylate racemization and acetolysis occur with the same degree of stereospecificity. Because of the symmetry properties of the *erythro* system, the same type of information is not available. However, the *erythro*-2-phenyl-3-pentyl and *erythro*-3-phenyl-2-pentyl tosylates clearly interconverted faster than they underwent acetolysis (ref. 7). This fact indicates that *erythro*-3-phenyl-2-butyl tosylate undoubtedly rearranged to itself faster than it acetolyzed.

The results in formic acid are much more stereospecific. This is partially due to the fact that, in this more dissociating solvent, the rate of racemization of L-*threo*-3-phenyl-2-butyl tosylate is only about a third that of formolysis. Thus 75% of the formate produced must come from optically pure tosylate, and 25% from racemized tosylate.

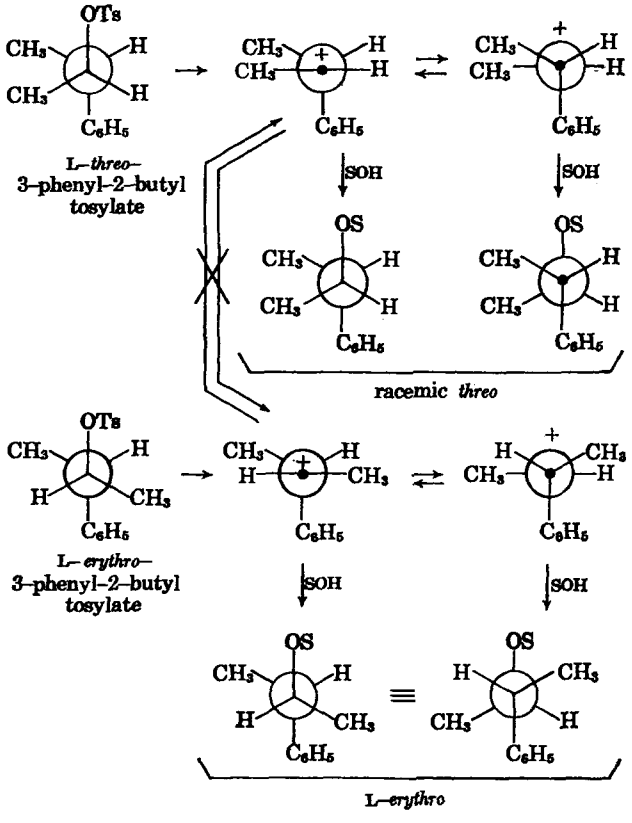
(7) D. J. Cram, *J. Am. Chem. Soc.*, **74**, 2159 (1952).

(8) W. B. Smith and M. Showalter have confirmed this fact with isotopic labeling experiments with both *erythro*- and *threo*-3-phenyl-2-butyl tosylate (private communication).

(9) If the correction of footnote 6 is applied, a 98.7% figure is calculated.

threo-3-phenyl-2-butyl system, solvent capture *from the side of the leaving group* would have to occur 24 times[10] as often as from the opposite side in acetic acid. In formic acid, the factor would have to be about 10,000. (3) For that material which does rearrange, the following sequence of events would have to be assumed. An open carbonium ion would have to be formed only from a conformation which places phenyl and tosyl groups *trans* to one another in the starting material, irrespective of which diastereomer is used. An unrearranged open carbonium ion would have to equilibrate with a rearranged carbonium ion much faster than any

CHART I



conformational interconversions could occur. The rearranged open carbonium ion would then have to react with solvent faster than any conformational interconversions could take place, and the solvent would have to become bonded only from the face of the carbonium ion *trans* to the phenyl group. In the acetolysis of the diastereomers of the 3-phenyl-2-butyl system, these stereospecific processes would have to dominate over nonstereospecific processes by about factors of 25.[10] In formolysis, the factor would have to be about 10,000.

Classical carbonium ion theory itself conflicts with this complex series of assumptions. For example in acetolysis of simple secondary tosylates, net inversion is the standard result,[11] rather than the high retention observed with all the diastereomers of the 3-phenyl-2-butyl and the two phenylpentyl systems. Open carbonium ion theory also would require higher stereospecificity in the more nucleophilic and less dissociating solvent, acetic acid. Experimentally, with the 3-phenyl-2-butyl system, formolysis occurred with much higher stereospecificity than acetolysis. Rate ratios of stereospecific to nonstereospecific reactions were about 100 times higher valued in formic acid.

The principles of conformational analysis as applied to carbonium ion theory are also in serious conflict with the above assumptions. The conformation for *threo*-3-phenyl-2-butyl tosylate shown in Chart I should not be the most stable, nor should that of the derived carbonium ion. In each case, the effectively largest group on the "forward" carbon is methyl, and this is between the two largest groups on the "distant" carbon. *No theory and no analogy from classical carbonium ion chemistry is available which explains why this conformation of the starting material should be the most reactive by a large factor in acetic acid, and be almost the exclusive form to react in formic acid.* No theory or analogy based on classical carbonium ion behavior explains why migration should occur much faster than solvent capture, or why solvent capture should occur exclusively from only one face, or why both of these latter processes should proceed faster than rotation about the central carbon–carbon bond. *The appendage of the assumption of two rapidly equilibrating open ions to classical carbonium ion theory in no way controverts these statements*, and provides no explanation of why so little leakage occurs between the *threo* and *erythro* series.

The results of deamination of optically pure *threo*- and *erythro*-3-phenyl-2-butylamine in acetic acid provide a picture of ground state conformational control of products in the 3-phenyl-2-butyl system.[12] Thus *threo*-amine gave acetate, 32% of which involved methyl migration, 24% hydrogen migration, 12% phenyl migration, and the remaining 32% acetate, which did not rearrange, was 15% of retained and 17% of inverted configuration. The *erythro*-amine gave acetate, 6% of which involved methyl migration, 20% hydrogen migration, and 74% of combined product of phenyl rearrangement and nonrearrangement. Of this latter fraction, 68% was of retained and 6% of inverted configuration. These results are consistent with the principles of conformational analysis applied to open carbonium ions.

Clearly, classical carbonium ion theory is in conflict on many counts with the behavior of the three tosylate systems, and open carbonium ions can be rejected as the dominant intermediates in the solvolyses.

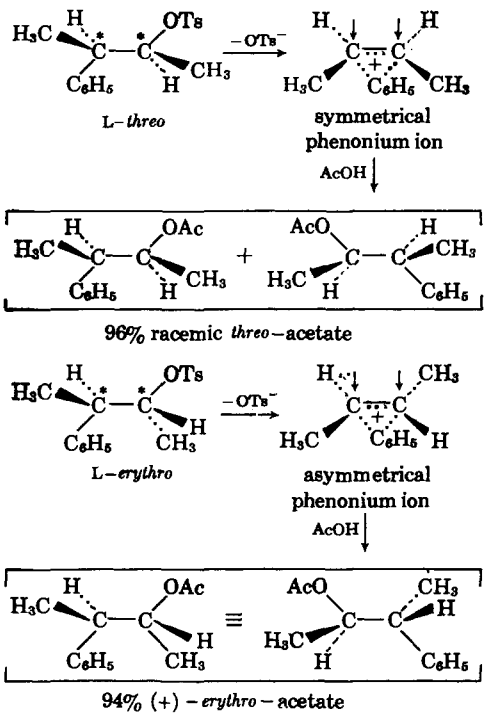
In contrast, all the facts are economically accommodated by invoking bridged ions as discrete intermediates in the solvolytic reactions (see Chart II). In this scheme, the phenyl group assists from the back in the ionization of the tosylate and forms a phenonium ion, which is consumed by solvent attack at either of the bridged carbon atoms from the side originally occupied by the tosylate group. This mechanism explains why active *threo*-3-phenyl-2-butyl tosylate provides racemic *threo*-acetate or formate with very little crossover into the *erythro* series. Likewise, it accounts for the production of active *erythro*-acetate or formate from active *erythro*-tosylate with very little production of *threo* isomer. All the results of the two phenylpentyl systems are also accounted for by similar bridged ion theory.

(10) If the correction of footnote 6 is applied, this number becomes 96.

(11) A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, pp. 59 and 73.

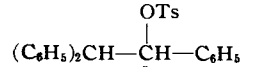
(12) D. J. Cram and J. E. McCarty, *J. Am. Chem. Soc.*, **79**, 2866 (1957).

CHART II



The higher stereospecificity of the formolyses as compared to the acetolyses is equally consistent with bridged carbonium ion theory. Phenyl as a nucleophile competes with solvent, and direct solvent intervention in ionization leads to crossover from *threo* to *erythro* material, or *vice versa*. The greater nucleophilicity of acetic over formic acid explains why more crossover was observed in acetic than in formic acid.

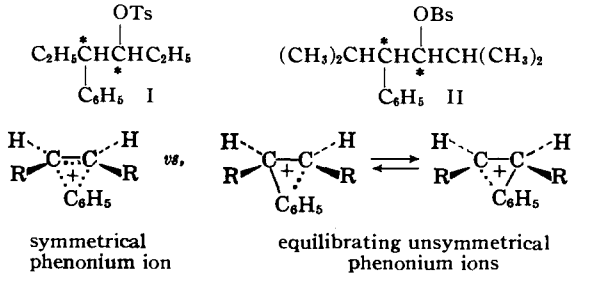
Brown has offered no explanation for the above stereochemical results whatsoever, yet he states[2] in reference to the phenonium ion in the 3-phenyl-2-butyl system "it should be recognized that the observed results do not *require* that the solvolysis proceeds through such an intermediate. Attention is called to the 1,2,2-triphenylethyl system where the solvolysis proceeds with predominant retention even though the reaction involves open classical carbonium ions." Here he refers to the work of Collins and Bonner,[13] who carefully demonstrated that neither phenyl participation nor phenonium ion intermediate was *required* to explain a large body of solvolytic data for 1,2,2-triphenylethyl tosylate, some of which demonstrated that the phenyl groups migrated. These authors observed that acetolysis occurred with 8–16% net retention (92–84% racemization), and explained their results in terms of conformational analysis of open carbonium ions. The vast difference in the stereochemical behavior of *threo*-3-phenyl-2-butyl and 1,2,2-triphenylethyl systems can be summarized by the statement that the former was 29 times more stereospecific at each of two asymmetric centers in its reactions than the latter system was at a single center.[14] Actually, if the result obtained in the 1,2,2-triphenylethyl system reflects normal behavior of open carbonium ions of classical theory, the strikingly different result observed for the *threo*-3-phenyl-2-butyl system requires some new theory, and bridged carbonium ion theory fills this need.



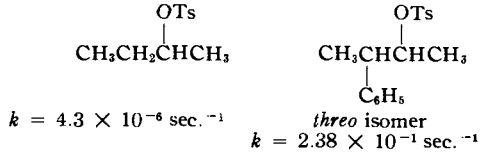
1,2,2-triphenylethyl tosylate

Extensive studies were made of all isomers of systems I and II in hopes of differentiating between a single symmetrical phenonium ion and two rapidly equilibrating but unsymmetrical phenonium ions.[15] It was thought that the eclipsing effects of two ethyl or two isopropyl groups in a *cis*-phenonium ion might be great enough to require two equilibrating unsymmetrical phenonium ions to intervene in the rearrangement. No definitive result was obtained which would allow a choice to be made between a single symmetrical phenonium ion or two unsymmetrical but equilibrating bridged ions. In the absence of conclusive evidence which favors two bridged ions over one, and in the interests of economy of theory, the symmetric phenonium ion is preferred for potentially symmetrical systems.[16]

As was indicated in the original investigation,[1b] the Wagner–Meerwein rearrangement with phenyl as migrating group amounts to an intramolecular electrophilic substitution of aryl by an alkyl tosylate. Heptamethylbenzenonium aluminum tetrachloride[17] represents the noncyclic counterpart of a phenonium ion.



Kinetic Evidence for Neighboring Aryl Participation in Ionization during Solvolysis.—The rates of acetolysis of 2-butyl tosylate and *threo*-3-phenyl-2-butyl tosylate at 50° are very close to one another.[18] These data



have been quoted by H. Brown[2] as not supporting phenyl participation in the ionization stage of the latter compound. Brown quoted the *dissociation* rather than the *ionization* rates, which are not identical in this system[5,19] because of "internal return." The ionization rate of 3-phenyl-2-butyl tosylate is about 3 times as great as the rate of ionization of 2-butyl tosylate.

(13) (a) W. A. Bonner and C. J. Collins, *J. Am. Chem. Soc.*, **78**, 5587 (1956); (b) C. J. Collins, W. A. Bonner, and C. T. Lester, *ibid.*, **81**, 466 (1959).

(14) If the correction of footnote 6 is applied, the stereospecificity factor becomes 116.

(15) (a) D. J. Cram and F. A. Abd Elhafez, *ibid.*, **75**, 3189 (1953); (b) D. J. Cram, H. L. Nyquist, and F. A. Abd Elhafez, *ibid.*, **79**, 2876 (1957).

(16) Unsymmetrically bridged ions are ions in which the bridging group is not equally bonded to the other two atoms which compose the three-membered ring. Such a situation is encountered in certain systems where the migration origin and terminus have different substituents.

(17) W. von E. Doering, M. Saunders, H. G. Boyton, H. W. Earhart, E. F. Wadley, W. R. Edwards, and G. Laber, *Tetrahedron*, **4**, 178 (1958).

(18) S. Winstein, B. K. Morse, E. Grunwald, K. C. Schreiber, and J. Course, *J. Am. Chem. Soc.*, **74**, 1113 (1952).

(19) S. Winstein and K. C. Schreiber, *ibid.*, **74**, 2165 (1952).

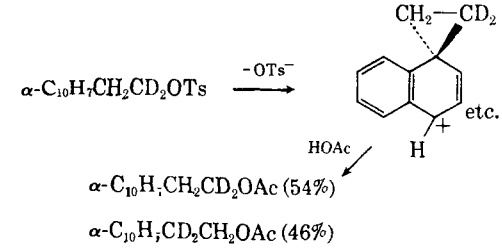
Brown also ignored the anticipated rate-retarding inductive effect of a phenyl substituent on the rate of solvolysis to produce a classical carbonium ion (estimated factor of 8 in acetic acid). When these factors are taken into account, the ionization of *threo*-3-phenyl-2-butyl tosylate is about 24 times what it would be if phenyl participation were absent.

Two other effects might further complicate the rate comparison of the 2-butyl and *threo*-3-phenyl-2-butyl tosylate systems. The added bulk of the phenyl in the latter system might provide steric acceleration of rate due to release of strain in ionization. On the other hand, introduction of a phenyl group into the 2-butyl system must provide steric inhibition of solvation of the transition states for ionization, and this effect is rate retarding. That the net effect is small is demonstrated by a comparison of the rates of acetolysis of *threo*-3-phenyl-2-butyl tosylate, *threo*-4-phenyl-3-hexyl tosylate (I), and *threo*-2,5-dimethyl-4-phenyl-3-hexyl brosylate (II).[15] If the rate data for II are corrected for the fact that brosylate and not tosylate ester is employed, and for temperature differences, the polarimetric rates (which measure rates of ionization) for the three systems differ by less than a factor of 2 and vary randomly. Substitution of two isopropyl groups for two methyl groups in an already somewhat hindered system should produce a larger steric effect than substitution of one phenyl for a hydrogen in an unhindered system. Since the net steric effect is trivial, the rate factor of 24 (see last paragraph) points to phenyl participation in ionization for 96% of the *threo*-3-phenyl-2-butyl tosylate which produces acetate. This value compares with one of about 99[10] calculated entirely from product and stereochemical data. Thus, the kinetic and stereochemical results are compatible, and provide a very strong case *both* for phenyl participation in ionization and for phenonium ions as discrete intermediates in these systems.

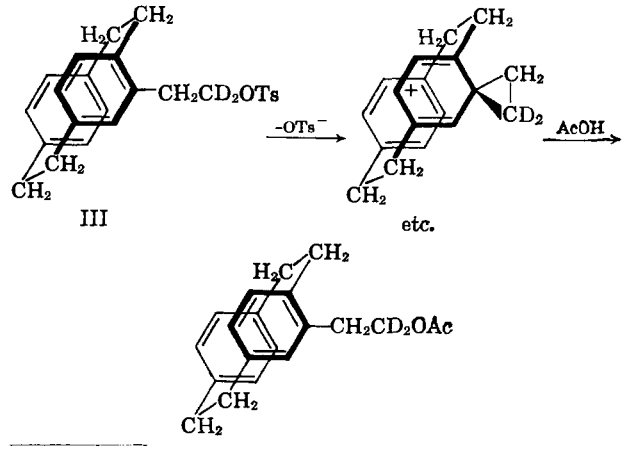
As noted by H.C. Brown,[2] ethyl tosylate acetolyzes 2.7 times as fast as β-phenylethyl tosylate (75°).[20] Through use of both C^{14} and deuterium isotope scrambling techniques,[21] it was found that only 5% rearrangement occurs in acetolysis of β-phenylethyl tosylate. The negative inductive effect of the phenyl group partially accounts for the factor of 2.7. The unhindered back side of the incipient carbonium ion allowed solvent to compete successfully with aryl in this medium. What Brown overlooked was the fact that in solvolysis in formic acid, *a less nucleophilic solvent*, β-phenylethyl tosylate reacted 2.1 times as fast as ethyl tosylate. If the 2.7 factor for the inductive effect obtained in acetolysis is applied to this result, a factor of 5.7 for phenyl over solvent participation is obtained. This result, based entirely on kinetics, is in accord with isotopic scrambling experiments[21b,c] which indicate that in formolysis phenyl participation is 9 times as important as direct reaction with solvent molecules.

Substitution of methyl groups in the 2,5-positions of the benzene ring of β-phenylethyl tosylate increased the acetolysis rate by a factor of 3.2[22] and increased rearrangement from 5 to 46%. Rearrangement was detected with deuterium labeling of the ethylene group. When a *p*-methoxyl group was substituted in β-phenylethyl tosylate, the rate of acetolysis increased by a factor of 30, and isotopic labels indicated 49% rearrangement.[21a] The above rate factors were uncorrected for either inductive effect or internal return, each of which would increase their values. The coupling of rate increase with the extent of rearrangement provides clear evidence for neighboring group assistance in ionization to form an intermediate which can partition between rearranged and unrearranged product. A bridged ion is such a species.

Other results indicate that in acetic acid, a naphthonium ion as intermediate accounts for the isotope scrambling of 2-(α-naphthyl)-1,1-dideuterioethyl tosylate.[23]



Neighboring aryl participation in ionization does not necessarily result in rearrangement. Use of [2.2]-paracyclophanyl as a neighboring group in the acetolysis of III provided a unique bridged ethylenephenonium ion which was unsymmetrical and was formed and opened for steric reasons only from the side remote from the transannular ring.[22] The deuterium label was therefore in the same place in both starting material and product. Evidence that aryl participated in ionization is found in the factor of 18 by which the rate of acetolysis of III exceeded that of β-phenylethyl tosylate. Other evidence derives from the fact that the entropy of activation for the acetolysis of III is −11.7 e.u. For a number of β-arylethyl systems ($ArCH_2CH_2X$) and solvents, neighboring group participation by aryl correlates with ΔS^* values of −9 to −12 e.u., and ionization with solvent participation correlates with values of −17 to −21 e.u.[21,22] The fact that III shows more driving force for aryl participation than its open-chain model, β-(2,5-dimethylphenyl)ethyl tosylate, is attributed to delocalization of positive charge into the transannular ring in the transition state for formation of the bridged ion from III.



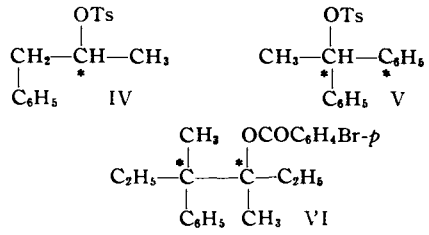
(20) S. Winstein, C. R. Lindegren, H. Marshall, and L. L. Ingraham, *J. Am. Chem. Soc.*, **75**, 147 (1953).

(21) (a) E. F. Jenny and S. Winstein, *Helv. Chim. Acta*, **41**, 807 (1958); (b) C. C. Lee, G. P. Slater, and J. W. T. Spinks, *Can. J. Chem.*, **35**, 1417 (1957); (c) W. H. Saunders, S. Asperger, and D. H. Edison, *J. Am. Chem. Soc.*, **80**, 2421 (1958).

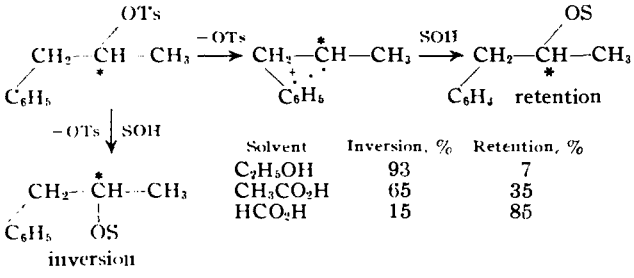
(22) D. J. Cram and L. A. Singer, *ibid.*, **85**, 1075 (1963).

(23) D. J. Cram and C. K. Dalton, *ibid.*, **85**, 1268 (1963).

Over 10 years ago, results of extensive studies were published on systems IV,[24a] V,[24b] and VI.[24c] In all

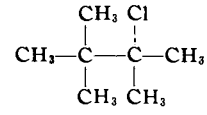


three systems, analysis of the products of solvolysis indicated that the extent of stereochemical control at the α-carbon exercised by the phenyl group was never high and was very much a function of solvent. No phenyl rearrangement occurred in IV and V during solvolysis, whereas VI rearranged with much, but not entire, loss of stereochemical control at the two asymmetric centers. Clearly, in these three systems open carbonium ions and phenonium ions are so close together in energy that changes in solvent can tip the balance between the relative rates of direct formation of the two types of ions. For example, IV gives predominant inversion at the α-carbon in ethanol, but predominant retention in the less nucleophilic solvent, formic acid.[24a] No open carbonium ion theory or pair of equilibrating open carbonium ions explains these results.

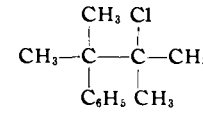


Solvent	Inversion, %	Retention, %
C_2H_5OH	93	7
CH_3CO_2H	65	35
HCO_2H	15	85

In 1962, H. C. Brown[2] quoted unpublished work and stated that systems VII and VIII solvolyzed at similar rates in 80% aqueous ethanol at 25°. He concluded that phenyl provides no assistance in ionization. The stereochemical behavior of VI, a homolog of VIII demonstrated long ago[24c] that phenyl participation was marginal in such systems. Thus in acetic acid, the *threo* and *erythro* system give product distributions which are not identical, but are very close to one another. The fact that VIII slightly exceeds VII in rate in spite of the rate-retarding inductive effect of the phenyl group probably reflects the greater steric compression in VIII as compared to VII. Some of this compression is released upon ionization.



VII, $k = 4.17 \times 10^{-2}$ hr.$^{-1}$



VIII, $k = 6.39 \times 10^{-2}$ hr.$^{-1}$

In 1952, Winstein, *et al.*,[18] noted the unusual reactivity of derivatives of β,β,β-triphenylethyl alcohol. These authors found that β,β,β-triphenylethyl tosylate (IX) acetolyzed at a rate about four powers of ten faster than ethyl tosylate. This observation was interpreted as evidence of *phenyl participation in ionization* of the tosylate. The authors pointed to both steric and electronic causes for the fast rate. The authors did not claim this fast rate was evidence for the existence of a phenonium ion. In reference to these authors, H. C. Brown states, "The nonclassical phenonium ion . . . . has also been utilized to account for the relatively fast solvolysis rate exhibited by β,β,β-triphenylethyl tosylate. . . ."[2] Brown then states that relief of steric strain may provide part or all of the driving force for rearrangement.[2]

$(C_6H_5)_3CCH_2OTs$
IX

The need for differentiation between the terms *neighboring group participation in ionization* and *bridged ions* (such as the phenonium ion) was never greater. The term *neighboring group participation in ionization* names a transition state which in principle could lead directly to a bridged ion, an open rearranged ion, or a rearranged stable product. Evidence for participation comes from rate comparisons or from stereochemical comparisons of starting materials and products, or both. *Bridged ions* name discrete intermediates. Evidence for their existence is stereochemical, not kinetic. Conceivably they could arise from either open ions or as a result of *neighboring group participation in ionization*. However, their stereochemical detection usually requires *neighboring group participation in ionization* for their formation.

Bridged and open carbonium ion theory complement one another and together provide a fabric of internal consistency and coverage of the facts. Either one alone fails to explain a great body of experimental data, only a little of which is discussed here.

(24) (a) S. Winstein, M. Brown, K. C. Schreiber, and A. H. Schlesinger, *J. Am. Chem. Soc.*, **74**, 1140 (1952); (b) F. A. Abd Elhalez and D. J. Cram, *ibid.*, **75**, 339 (1953); (c) D. J. Cram and J. D. Knight, *ibid.*, **74**, 5839 (1952).