Bridged Bromine and Chlorine Free-Radical Intermediates. Free-Radical Halogenations of 2-Halobutanes

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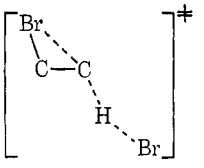
Abstract: Radical-chain halogenations of 2-bromo- and 2-chlorobutanes, optically active and deuterium substituted, provide insight into the nature of the radical intermediates. The 2,3-bromobutyl radical exists in two bridged forms, one optically active, the other inactive; they are produced in kinetically controlled hydrogen abstraction steps from (+)-(2*S*)-bromobutane. Either these intermediates have the bromine atom centered between C_2–C_3, or the bromine is not symmetrically disposed and moves between the extremes with frequency in excess of 10^{11} sec^{-1}. The 2,3-chlorobutyl radicals are bridged unsymmetrically and the excursion between the extremes occurs with frequency less than 10^8 sec^{-1}. Absolute configurations are assigned for (−)-(2*S*,3*S*)-dibromobutane, (−)-(2*R*)-bromo-(3*S*)-chlorobutane (*erythro*), (−)-(2*S*)-bromo-(3*S*)-chlorobutane (*threo*), (+)-(3*S*)-bromo-1-chlorobutane, and (−)-1-bromo-(2*R*)-chlorobutane. There is also described a method for partial resolution of the (±) halides, and for determination of their enantiomeric purity.

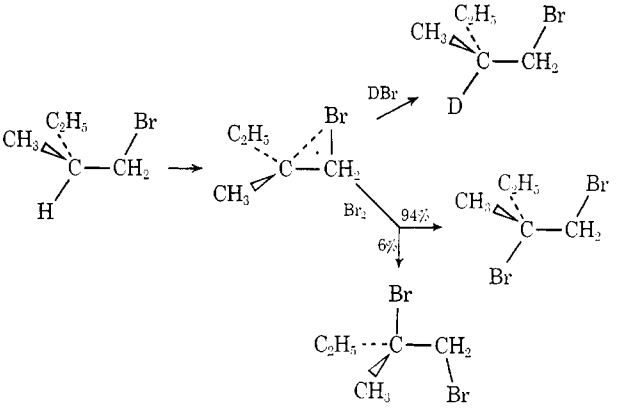
Gas phase free-radical chlorination and bromination of alkyl halides has been studied by a number of groups to determine the influence of substituents on the rate of hydrogen abstraction.[2,3] In all reports, the positions β to the halogen are deactivated.

However, Thaler[4] reported that although solution phase bromination and chlorination of 1-chlorobutane and chlorination of 1-bromobutane all showed this same behavior, bromination of 1-bromobutane gave the 1,2-dibromide as the principal product. The reactivity of carbon-2 was 5.78 times that of carbon-3. This anomalously high reactivity of β hydrogens of bromoalkanes for free-radical bromination has been found in a number of other cases.[5–8] These results have been interpreted in terms of anchimeric assistance by the neighboring bromine susbstituent in the rate limiting hydrogen abstraction step.[4–10]



Where bromine bridging occurs the stereochemical course of the reaction is controlled.[9–12] Thaler reported photobromination of bromocyclohexane gave about 90% *trans*-1,2-dibromocyclohexane, substitution at other positions in the ring accounting for the remainder of product; the *cis*-1,2-dibromide was not detected. Skell and Readio[9] observed photobromination of optically active 1-bromo-2-methylbutane gave 1,2-dibromo-2-methylbutane having high optical purity. If the system contains a large amount of deuterium bromide, a second product is 1-bromo-2-deuterio-2-methylbutane with optical purity nearly identical with that of the starting material.[13]

Control of product stereochemistry in reactions involving β-bromoalkyl radicals has been attributed to formation of a discrete bridged free-radical intermediate. It was shown that the bridged intermediate, when it is structurally unsymmetrical and it is produced as a single enantiomer, has a lifetime long enough to permit trapping with high stereoselectivity by molecular bromine[9] or deuterium bromide[13] without loss of optical purity. To account for these stereochemical results and the failure to form *cis*-1,2-dibromide from



cyclohexyl bromides, a backside attack of bromine (or DBr) on the bridged intermediate was proposed. In these cases there is a strong preference for reaction at one of the carbon atoms of the bridge, implicating unsymmetrical bridging.

The present study of the photohalogenation of 2-halobutanes was undertaken to obtain further insight into the influence of β-halogen substituents on the course of free-radical halogenations, and to test the proposals discussed above. It will be shown that the results cannot be explained with a classical β-haloalkyl radical, but require the transition states and bridged intermediates shown above.

(1) Author to whom correspondence should be sent.
(2) W. A. Thaler, "Methods in Free-Radical Chemistry," Vol. 2, E. S. Huyser, Ed., Marcel Dekker, New York, N.Y., 1969, p 127.
(3) M. Poutsma, ref 2, Vol. 1, 1968.
(4) W. A. Thaler, *J. Amer. Chem. Soc.*, **85**, 2607 (1963).
(5) P. S. Skell and P. D. Readio, *ibid.*, **86**, 3334 (1964).
(6) P. S. Skell and K. J. Shea, *ibid.*, **94**, 6550 (1972).
(7) J. G. Traynham and W. G. Hines, *ibid.*, **90**, 5208 (1968).
(8) J. G. Traynham, E. E. Green, Y. Lu, F. Schweinsberg, and C. Low, *ibid.*, **94**, 6552 (1972).
(9) P. S. Skell, *Chem. Soc., Spec. Publ.*, **No. 19**, 131 (1964).
(10) P. S. Skell, D. L. Tuleen, and P. D. Readio, *J. Amer. Chem. Soc.*, **85**, 2850 (1963).
(11) P. S. Skell and K. J. Shea, *Isr. J. Chem.*, **10**, 493 (1972).
(12) P. S. Skell and K. J. Shea, "Free Radicals," J. K. Kochi, Ed., Wiley-Interscience, New York, N. Y., in press.
(13) K. J. Shea and P. S. Skell, *J. Amer. Chem. Soc.*, **95**, 283 (1973).

Results and Discussion

Photobrominations of *erythro*- and *threo*-3-Deuterio-2-bromobutanes. The liquid phase photobromination of 2-bromobutane was originally reported by Thaler;[4] the diastereomeric 2,3-dibromobutanes amount to 83.7% of the product, 2,2-dibromobutane (16.3%) the remainder. Our results are in agreement with this finding (Table II), 2,3-dibromobutanes comprising 85.1% of the reaction products. The ratio of *meso*-/*d,l*-2,3-dibromobutane is 2.5.

If a classical 2-bromo-3-butyl radical ($CH_3\dot{C}HCH$-$BrCH_3$) were the intermediate in this reaction, the relative amounts of *meso*- and *d,l*-2,3-dibromobutane would be determined in the second step of the reaction, trapping by Br_2. Bromination of either of the diastereomeric 3-deuterio-2-bromobutanes therefore should give the same ratio of 2,3-dibromides as the undeuterated 2-bromobutanes. The ratios of dibromides from the photobromination of *erythro*- and *threo*-3-deuterio-2-bromobutane together with 2-bromobutane are given in Table I. The large variations in the *meso*/*d,l* ratios require that there be more than a single intermediate in the reaction.

Table I. Ratio of Diastereomeric 2,3-Dibromobutanes from the Photobromination of 2-Bromobutanes[a]

Starting material	*meso*/*d,l*
2-Bromobutane	2.5
erythro-3-Deuterio-2-bromobutane	0.61
threo-3-Deuterio-2-bromobutane	6.50

[a] 0.2 *M* bromine with NBS in $CFCl_3$ at 15°, photoinitiated.

The isotopic labeling of the products from the photobromination of 3-deuterio-2-bromobutanes is summarized in Table II.

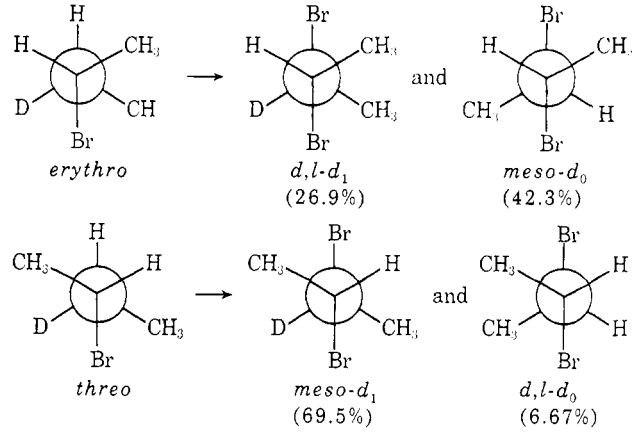
Table II. Dibromobutane Composition from the Photobromination of 3-Deuterio-2-bromobutanes[a] (Normalized Yields)[b]

Reactant	2,2-Dibromobutane	*meso*-d_0	*meso*-d_1	*d,l*-d_0	*d,l*-d_1
2-Bromobutane	14.9	60.7		24.3	
erythro-3-Deuterio-[c]	29.1	26.9	(−0.1)	(1.63)	42.3
threo-3-Deuterio-[c]	18.9	(1.9)	69.5	6.67	(4.43)

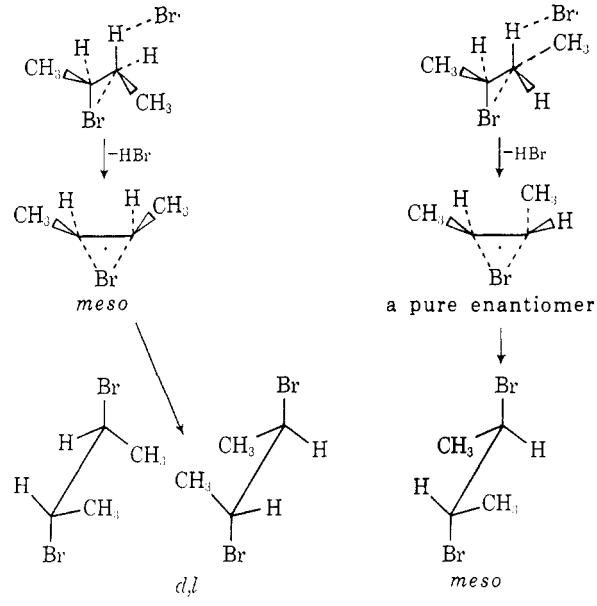
[a] 0.2 *M* bromine and NBS in $CFCl_3$ at 15°. [b] Per cent of dibromide products. [c] *erythro*- and *threo*-3-deuterio rows are corrected by iterative procedure for undeuterated and diastereomeric impurities in the starting material.

If the values in parentheses (Table II) were zero, the reactions would be classified stereospecific. Although these values are not zero, they are small and may in fact be zero; the major reactions occur with retention of configuration, with less crossover than 1.6% from the erythro and 6.2% from the threo isomer. This radical chain bromine substitution reaction must be described as largely, or wholly, stereospecific.

If $CH_3CHBr\dot{C}H(D)CH_3$ had been the intermediate, large extents of crossover would have been expected, and the *meso*/*d,l* ratio would have been the same, regardless of labeling of the 2-bromobutane.



These results can be explained if (1) H-abstraction by bromine atom occurs with assistance by the neighbor bromine substituent in an antiperiplanar configuration, and (2) the bridged intermediate is trapped by Br_2 faster than it isomerizes. The relative rates of formation of these bridged intermediates will be altered by the presence of an H or D at the abstraction site.



This scheme differs from the usual radical-chain halogenation mechanism in that product stereochemistry is fixed in the hydrogen atom abstraction step rather than in the second step, trapping of the alkyl radical by Br_2.

From the data in Table II the relative rates of bromination can be calculated for the pure compounds: 2-bromobutane (1.00); *threo*-3-deuterio-2-bromobutane (0.82); *erythro*-3-deuterio-2-bromobutane (0.55).

The kinetic isotope effect for hydrogen atom abstraction by bromine atoms can be obtained by comparison of the ratios of *d,l* to *meso* products from the undeuterated and deuterated substrates. Assuming the secondary isotope effect is 1.00, the rates of hydrogen loss from 2-bromobutane and *erythro*-3-deuterio-2-bromobutane to form *d,l* products are identical and thus serve as internal standards for comparing the yields of the *meso* products (data from Table I). For the route to *meso*-2,3-dibromobutane (15°)

$$(k_H/k_D)_{meso} = (meso/d,l)_{2\text{-bromobutane}}(d,l/meso)_{erythro} = 3.9$$

Similarly, the isotope effect for the route to *d,l*-2,3-dibromobutane (15°) is

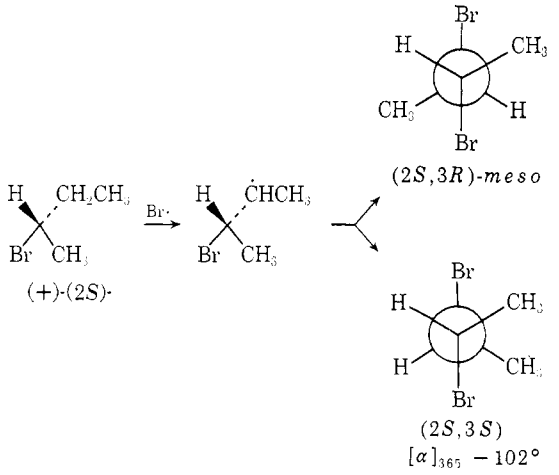
$$(k_H/k_D)_{d,l} = (d,l/meso)_{2\text{-bromobutane}}(meso/d,l)_{threo} = 4.2$$

There have only been a few primary deuterium isotope effects reported for free-radical brominations.[14,15] The values of Wiberg and Slaugh[15b] are more recent and are claimed to be more accurate. The primary isotope effect for toluene (k_H/k_D = 4.9, 77°) is higher than our value for acyclic 2° hydrogen abstractions at 15° (above). The toluene isotope effect may indeed be nearly maximal since the hydrogen abstraction from toluene is approximately thermoneutral; it is not clear that the 2-bromobutane values indicate either more or less bond-stretching in the transition state. Further, the $\Delta S^{\ddagger}$ are undoubtedly different for these two reactions.[16] A recent report of a primary deuterium isotope effect for allylic hydrogen abstraction by bromine atoms gave k_H/k_D = 2.09.[17]

Photobromination of (+)-(2*S*)-Bromobutane. The photobromination results of the 3-deuterio-2-bromobutanes are best understood in terms of a bromine assisted hydrogen abstraction leading to a bridged bromine free radical. Further evidence for the proposal is obtained from the photobromination of (+)-(2*S*)-bromobutane.

The "classical" radical mechanism (Scheme I)

Scheme I. Classical Radical

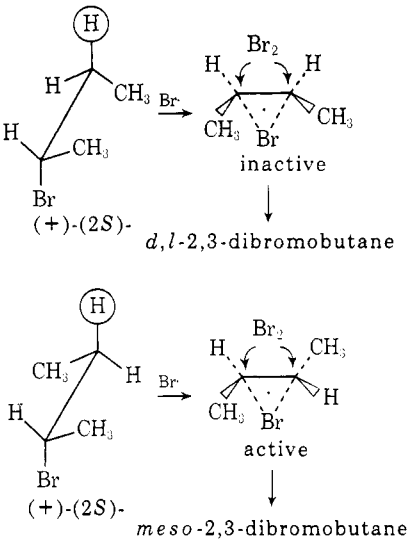


predicts that the asymmetric carbon atom of 2-bromobutane should be untouched during the photobromination reaction: photobromination of (+)-(2*S*)-bromobutane should produce pure (−)-(2*S*,3*S*)-dibromobutane and (2*S*,3*R*)-2,3-dibromobutane (*meso*); no (+)-(2*R*,3*R*)-dibromobutane should be formed.

On the other hand, a bridged radical mechanism (Scheme II) with only backside attack by Br_2 predicts formation of (2*S*,3*S*)- and (2*R*,3*R*)-dibromobutanes in equal quantities, since the bridged intermediate that produced these compounds has a plane of symmetry. Although the radical that should lead to the *meso* compound is dissymmetric, the product has a plane of symmetry. Both bridged routes lead to inactive product.

(14) W. H. Urey, Abstracts Twelfth National Symposium, Denver, Colo., 1951, p 30.
(15) (a) K. B. Wiberg, *Chem. Rev.*, **55**, 713 (1955); (b) K. B. Wiberg and L. H. Slaugh, *J. Amer. Chem. Soc.*, **80**, 3033 (1958).
(16) J. A. Kerr, *Chem. Rev.*, **66**, 465 (1966).
(17) J. S. Incremona and J. C. Martin, *J. Amer. Chem. Soc.*, **92**, 627 (1970).

Scheme II. Bridged Radical



Experimentally it was observed that the *d,l*-2,3-dibromobutane produced by photobromination of (+)-(2*S*)-bromobutane was extensively racemized, that is (2*S*,3*S*)- and (2*R*,3*R*)-2,3-dibromobutane were produced in almost equal amounts. At 1.25 *M* bromine concentration, photobromination of (+)-(2*S*)-bromobutane ($[\alpha]^{25}_{365}$ +115.7°, 80.1% optical purity) gave 2,3-dibromobutanes (*meso*/*d,l* = 2.5) in 89.1% yield. After correcting to optically pure starting material, *d,l*-2,3-dibromobutane had a rotation of $[\alpha]^{20}_{365}$ −5.2°. This corresponds to 95% racemic product, optically pure (−)-(2*S*,3*S*)-dibromobutane, $[\alpha]^{20}_{365}$ −102° (*vide infra*). The optical activity of the *d,l*-2,3-dibromobutane did not change over a 100-fold decrease in bromine concentration. The origin of this small amount of optically active product is being investigated.

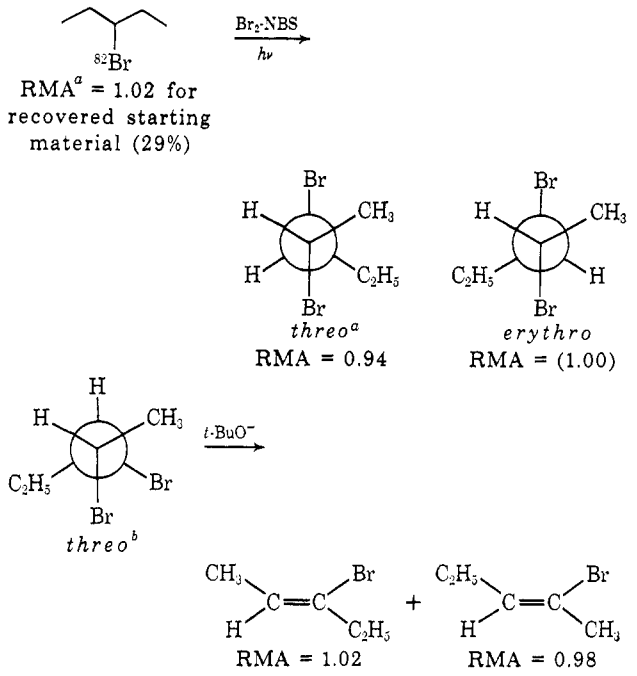
The reaction conditions do not have a significant effect on the enantiomeric purity of the starting materials or products.

If one ignores for the moment the small component of this reaction which leads to active product, the major reactions are rationalized by Scheme II.

Radioactive Labeling Experiment. One predicted property of a symmetrical bridged radical, such as is proposed for the 2-bromobutane system, is that the bromine originally in the starting bromoalkane will become statistically distributed between the original position and the adjacent one. Rather than do the required doubling labeling experiment, the bromination of 3-bromopentane-^{82}Br to the 2,3-dibromopentanes was studied.

Photobromination of radioactive 3-bromopentane-^{82}Br with ordinary Br_2 led to a mixture of *erythro*- and *threo*-2,3-dibromopentanes (Scheme III). Base dehydrohalogenation of the *threo*-2,3-dibromopentane showed the original bromine atom was evenly distributed between the 2 and 3 positions in the product. These experiments show that the ^{82}Br originally present in the starting material was distributed equally between the 2 and 3 carbons; thus photobromination of 3-bromopentane proceeds through either a bridged radical or an intermediate where 1,2-bromine atom migration occurs faster than trapping by molecular bromine. If there had been no bridged intermediate, all of the activity would have remained at C_3.

Scheme III



[a] RMA = relative molar radioactivity: (counts/mmol)/(counts/mmol) std. [b] The bromoolefins from dehydrohalogenation of the erythro diastereomer could not be separated.

Elimination of Br from the bromopentyl radical is a minor reaction. After 83% conversion of the labeled 3-bromopentane the unreacted Br_2 had acquired 8% of the activity. However, much of this activity in the Br_2 was demonstrated, by examining the inverse labeling experiment, to originate from a displacement reaction on 3-bromopentane. Reaction of labeled Br_2 with unlabeled 3-bromopentane introduced 6% of label in the starting material after 72% conversion to the dibromide.

Photochlorination of (+)-(2*S*)-Bromobutane with *tert*-Butyl Hypochlorite. Photobromination of (+)-(2*S*)-bromobutane gives two bridged bromine intermediates, one inactive (cis) which leads to *d,l*-2,3-dibromobutane, the other active (trans), which gives *meso*-2,3-dibromobutane. If these same intermediates were generated in the presence of a trapping agent other than bromine, an optically active product would be expected to result from the optically active (trans) bridged free-radical intermediate. This proposal was tested by the free-radical chlorination of (+)-(2*S*)-bromobutane. The results from this reaction are summarized in Table III.

threo-2-Bromo-3-chlorobutane is optically inactive while the erythro isomer is formed with a high degree of optical purity. These results are explained by hydrogen abstraction from the 3 position in (+)-(2*S*)-bromobutane to give the cis- and trans-bridged intermediates, and subsequent trapping from the backside by *tert*-butyl hypochlorite (Scheme IV). From an open chain radical, or an unsymmetrically bridged, but nonequilibrating radical intermediate, both products should have been obtained enantiomerically pure.

The substitution at the asymmetric carbon yields racemic 2-bromo-2-chlorobutane.[18]

A further interesting result from this study was the failure to observe 1-chloro-2-bromobutane, the product

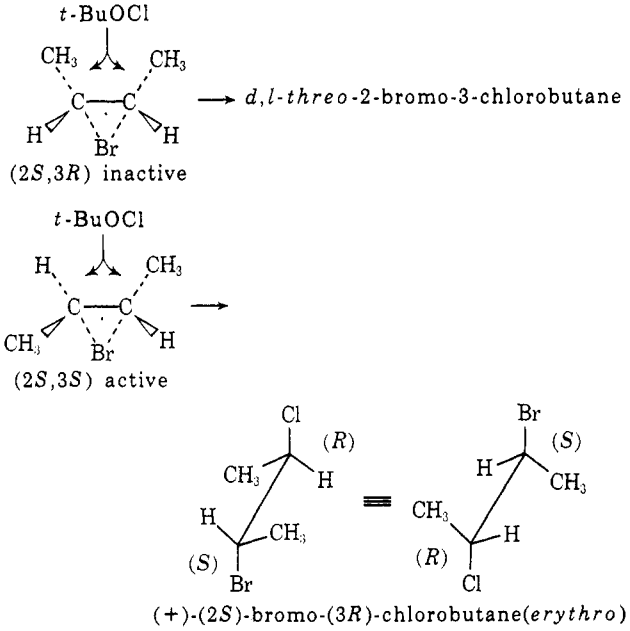
(18) The small rotations could be due to contamination by small amounts of optically active products.

Table III. Photochlorination of (+)-(2*S*)-Bromobutane[a] with *tert*-Butyl Hypochlorite

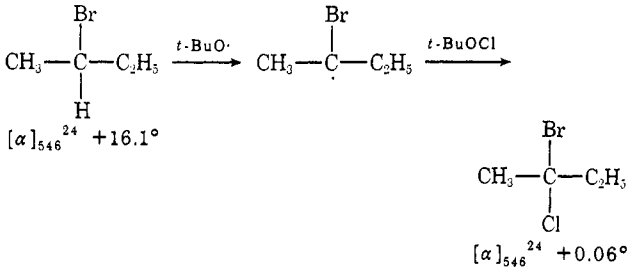
Product	Yield, %	$[\alpha]^{25}_{546}$,[b] deg	Enantiomeric purity, %[b]
2-Bromobutane	*c*	*d*	97.4
2-Bromo-2-chlorobutane	52.8	+0.06[e]	0
erythro-2-Bromo-3-chlorobutane	20.3	+7.8[f]	Probably optically pure[g]
threo-2-Bromo-3-chlorobutane	6.1	+0.4[h]	1[i]
1-Bromo-2-chlorobutane	3.2	−34.5[j]	Probably optically pure[k]
1-Chloro-3-bromobutane	4.1	+38.5[l]	100
Dichlorobromobutane	13.4		

[a] $[\alpha]^{25}_{546}$ +16.1° (neat), 38.8% optical purity. [b] Corrected to optically pure starting material. [c] Recovered starting material, 16%. [d] Starting bromide, α^{25}_{546} 20.28° (neat); recovered, α^{25}_{546} 19.58° (neat), 1 dm. [e] Neat, α^{25}_{546} +0.02° (1 dm). [f] 81.2 g/100 ml, 1-bromobutane, α^{25}_{546} +2.44° (1 dm). [g] See text. [h] 9.7 g/100 ml, 1-bromobutane, α^{25}_{546} +0.015° (1 dm). [i] Based upon calculated rotation for the pure enantiomer, $[\alpha]_{546}$ 40°. [j] 7.4 g/100 ml, 1-bromobutane, α^{25}_{546} −0.99° (1 dm). [k] The rotation of the pure enantiomer is not known; however, the magnitude of rotation compared with the rotation of other pure enantiomorphs (*e.g.*, 1-chloro-3-bromobutane, $[\alpha]^{25}_{546}$ +38.5°) suggests the compound is a pure enantiomer. [l] 16.0 g/100 ml, 1-bromobutane, α^{25}_{546} +2.39° (1 dm).

Scheme IV

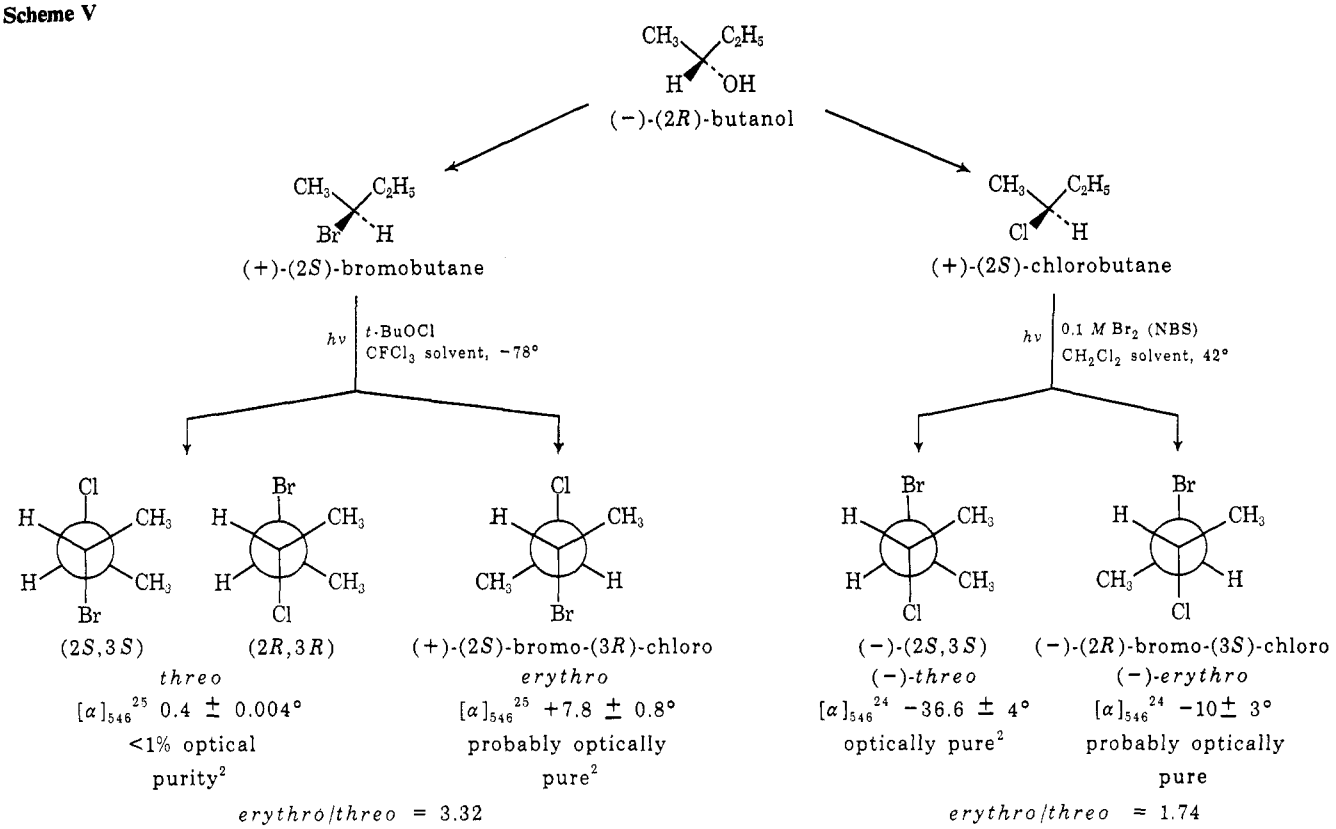


resulting from hydrogen abstraction at the 1 position. The only product observed from hydrogen abstraction at C-1 is 1-bromo-2-chlorobutane, *a rearrangement product, with a high optical rotation!*



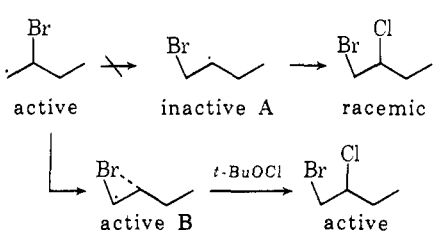
Although no hard evidence is available to substantiate the configuration and optical purity of this product,

Scheme V



the configuration can be inferred with reasonable confidence. The (+)-3-bromo-1-chlorobutane must have *S* configuration, and it is produced with 100% optical retention. The structurally similar (−)-1-bromo-2-chlorobutane is then assigned *R* configuration.

Free-radical rearrangements of halogen atoms (Br and Cl) are well known.[9,19,20] The formation of 2-bromo-1-chlorobutane can result from rearrangement of the 2-bromo-1-butyl radical *via* a bridged transition state to the intermediate 1-bromo-2-butyl radical (A) or *via* a bridged free-radical intermediate (B) which is trapped before opening to A. Only the latter possibility explains the formation of a rearranged optically active product.[21] This scheme predicts the product is (−)-1-bromo-(2*R*)-chlorobutane. The unsymmetrical bridging of the intermediate is suggested to explain the absence of 2-bromo-1-chlorobutane.



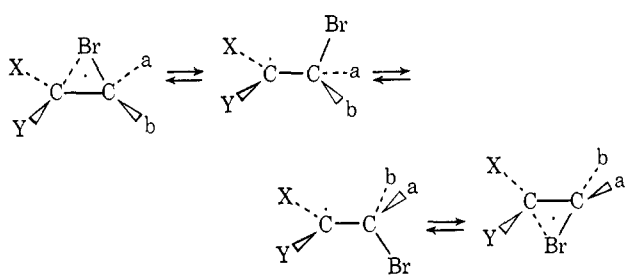
It is noteworthy that in this experiment three different bridged radicals are trapped by *tert*-butyl hypochlorite prior to racemization, a result to be contrasted with the extensive racemization observed in the analogous chlorination of 1-bromo-2-methylbutane.[9]

(19) R. Kh. Freidlina, *Advan. Free-Radical Chem.*, **1**, 211 (1965).

(20) (a) P. S. Skell, R. G. Allen, and N. D. Gilmour, *J. Amer. Chem. Soc.*, **86**, 3334 (1964); (b) P. S. Juneja and E. M. Hodnett, *ibid.*, **89**, 5685 (1967).

(21) A dissociation–readdition mechanism, involving an olefin intermediate, would of course predict a racemic product, and is thus excluded.

This speaks for faster racemization of a radical with bromine bridging between a primary and tertiary site than between primary and secondary sites. Thus, the more stable the classical radical, the more readily does the bridged radical racemize by ring opening and rotation about the C–C axis.



Photobromination of (+)-(2*S*)-chlorobutane produces as the major product (±)-2-bromo-2-chlorobutane. The minor products, the *erythro*- and *threo*-2-bromo-3-chlorobutanes, were isolated in such small quantities as to put large error limits on their observed rotations. However, within those limits *both* are enantiomerically pure (see Table IV). These results contrast with those from the chlorination of (+)-(2*S*)-bromobutane in which only the erythro product was enantiomerically pure, the threo being racemic (see Scheme V).

While the experiment with 2-bromobutane required a bridged intermediate which was trapped only after C_2 and C_3 had become indistinguishable, two alternative explanations must be considered for the 2-chlorobutane experiment (see Scheme VI). One possibility is that there is no bridging of the chlorine between C_2 and C_3 (no rearrangement), and a classical 3-chloro-2-butyl radical is the intermediate (left side of scheme). This hypothesis is rejected because it would require a

Scheme VI

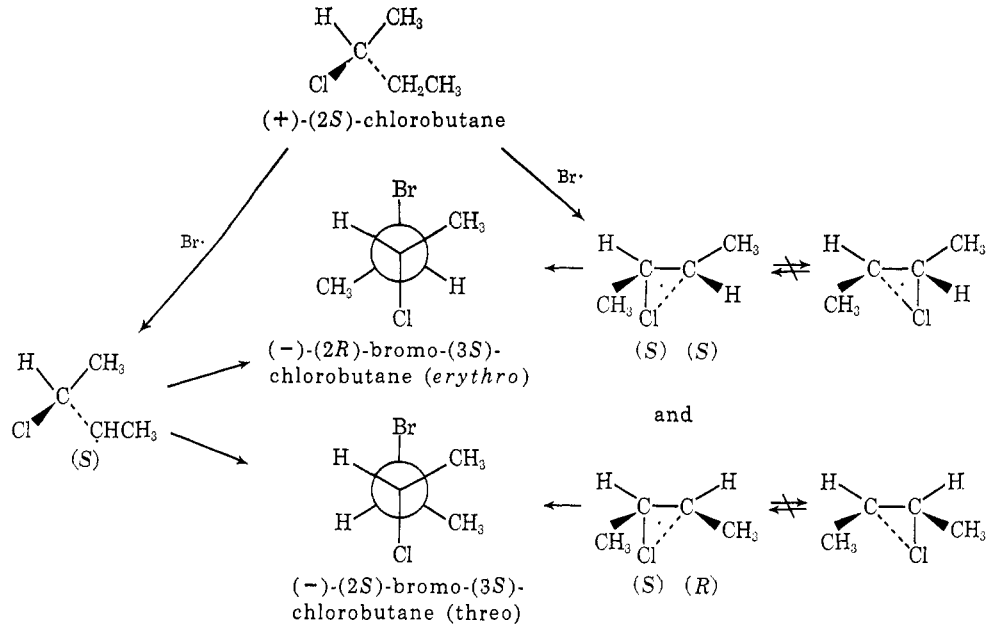


Table IV. Photobromination of (+)-(2*S*)-Chlorobutane[a]

Product	Yield, %	α (0.01 dm),[b] deg	$[\alpha]^{24}_{546}$,[b] deg	Optical purity, %
2-Chlorobutane	*c*	*c*		97.3
2-Bromo-2-chlorobutane	84.7	0.001[d]	0	0
erythro-2-Bromo-3-chlorobutane	9.74	0.003[f]	−10[e]	128 ± 30[g]
threo-2-Bromo-3-chlorobutane	5.58	0.0075[h]	−36.6	91.5 ± 10[i]

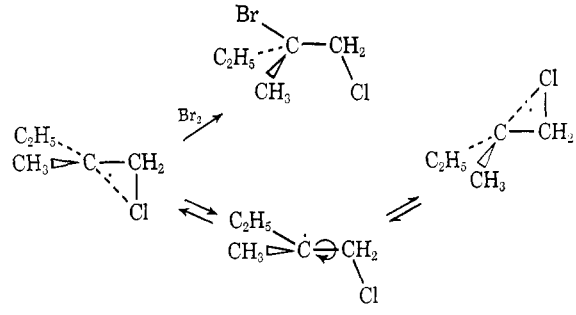
[a] $\alpha^{24}D$ +30.1° (1 dm, neat); 100% optically pure. [b] ±0.001°. [c] Recovered starting material, 45%, $\alpha^{24}D$ +0.298° (0.01 dm, neat). [d] Neat. [e] Neat, rotations at all wavelengths (5893–4050 Å) were less than 0.001°. [f] 3.75 g/100 ml, CCl_4. [g] Based upon highest observed rotation, $[\alpha]^{25}_{546}$ 7.8°. [h] 2.05 g/100 ml, CCl_4. [i] Based upon estimated rotation for the pure enantiomer, $[\alpha]^{25}_{546}$ 40° (*vide infra*).

different explanation for those instances where bridging is required for radicals which are formally β-chloroalkyls. A hypothesis, consistent with all the known characteristics of β-chloroalkyl radicals, is that bridging is unsymmetrical with respect to C_2 and C_3 (right side of scheme), and further that symmetrization between C_2 and C_3 is slow compared to trapping with 0.1 *M* Br_2. This bridging system has a double minimum in its potential energy curve.

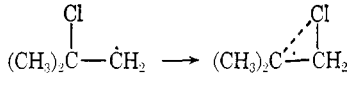
Three lines of evidence give strong support to the preference for bridged rather than classical β-chloroalkyl radicals.

(1) The photobromination of (+)-1-chloro-2-methylbutane produces, with retention of configuration, (−)-2-bromo-1-chloro-2-methylbutane of high enantiomeric purity if the configuration of Br_2 trapping agent is greater than 1 *M*.[9] The results are rationalized by the formation of an unsymmetrical chlorine bridge intermediate (racemization half-life, 10^{-10} sec) which reacts with Br_2 exclusively by inversion at the 2 position.

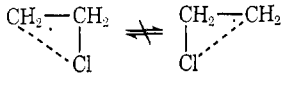
(2) Rearrangements occur in β-chloroalkyl radicals.[9] *tert*-Butyl chloride (^{36}Cl) is chlorinated (*t*-BuOCl) to 1,2-dichloro-2-methylpropane with ^{36}Cl on C_1. With



a more reactive trapping agent, *t*-BuOBr, less rearrangement occurs, and one derives a rate constant for rearrangement of the 2-chloroisobutyl radical to the 1-chloro-*tert*-butyl radical, $\sim 10^{10}$ sec^{-1}. This interpretation accords with the recent conclusions coming from interpretation of esr spectra in this system.[22,23]



(3) An interpretation of the esr spectrum of the β-chloroethyl radical which accounts for the low values of the hyperfine splittings and sharp line shapes includes an unsymmetrical chlorine bridge which does *not* interconvert on the esr time scale.[22-26]



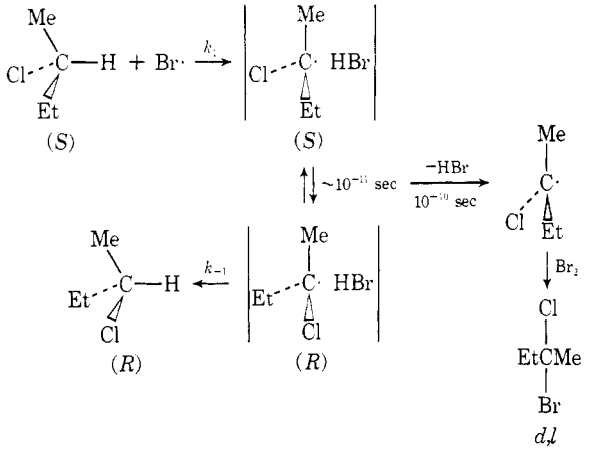
The major reaction product, 2-bromo-2-chlorobutane, which results from substitution at the asymmetric carbon, is racemic. With 0.1 *M* Br_2 as the trapping agent, the average lifetime of a radical is $\sim 10^{-9}$ sec.

(22) K. S. Chen, I. H. Elson, and J. K. Kochi, private communication.
(23) J. Cooper, A. Hudson, and R. A. Jackson, *Tetrahedron Lett.*, in press.
(24) A. J. Bowles, A. Hudson, and R. A. Jackson, *Chem. Phys. Lett.*, **5**, 552 (1970).
(25) A. R. Lyons and M. C. R. Symons, *J. Amer. Chem. Soc.*, **93**, 7330 (1971).
(26) (a) D. J. Edge and J. K. Kochi, *Tetrahedron Lett.*, 1341 (1972); (b) *J. Amer. Chem. Soc.*, **94**, 6485 (1972).

$$\underset{\text{optically pure}}{CH_3CHClCH_2CH_3} \xrightarrow{Br_2} \underset{[\alpha]^{24}{}^{\circ}{}_{546}\ 0.00^{\circ}}{CH_3CClBrCH_2CH_3}$$

The zero rotation observed indicates either a planar radical intermediate or, if pyramidal, it inverts with a frequency greater than 10^{11} sec^{-1} (based on <1% retention of optical purity). Further, this result precludes a mechanism in which Br_3 is the hydrogen abstracting agent[27] since under such circumstances the orientation of the alkyl radical to Br_2 in the cage would have dictated substantial retention of configuration.

The recovery of slightly racemized starting material gives an indication of the relative unimportance of cage recombination of R· and HBr formed from RH and Br. In the bromination of (+)-(2*S*)-chlorobutane in 0.1 *M* Br_2, 2-bromo-2-chlorobutane makes up 84.7% of the reaction products and conversion was over 50%. Nonetheless, the recovered starting material retained >97% of its original activity, indicating <6% of the 2-chloro-2-butyl radicals returned to 2-chlorobutane. Since rotations in nonassociated condensed phases occur with frequencies of 10^{11} sec^{-1}, and separation of nonbonded neighbor molecules requires on the average 10^{-10}–10^{-11} sec, then k_{-1} has a value *less than* 0.06 × 10^{10} to 0.06 × 10^{11} or 10^{9} to 10^{10} sec^{-1}. Since noncage HBr is kept at a negligible concentration by NBS,



it follows that under these bromination conditions cage reversal with HBr is a negligible path when compared with trapping of the radical by Br_2.

Absolute Configurations and Optical Rotations of Some Dihalobutanes. In order to obtain meaningful conclusions from a study of optically active compounds it is necessary to determine the absolute configurations and optical rotations of the enantiomers involved. For the main part these were not known.

2-Halobutanes. The absolute configuration of (−)-(2*R*)-butanol had been related to glyceraldehyde.[28] Reaction of (−)-(2*R*)-butanol with PBr_3, $(C_6H_5)_3PBr_3$, or with $(C_6H_5)_2PCl$ yields (+)-2-halobutanes. These reactions have been shown to occur with net inversion of stereochemistry.[29] Thus, the absolute configuration of a (+)-2-halobutane is *S*.

(27) See, for example, W. O. Haag and E. I. Heiba, *Tetrahedron Lett.*, 3679 (1965).

(28) K. B. Wiberg, *J. Amer. Chem. Soc.*, 74, 3891 (1952).

(29) (a) H. R. Hudson, *Synthesis*, 1, 112 (1969); (b) D. G. Goodwin and H. R. Hudson, *J. Chem. Soc. B*, 1333 (1968); (c) J. P. Schaeffer and D. S. Weinberg, *J. Org. Chem.*, 30, 2635 (1965); (d) G. A. Wiley, R. L. Hershkowitz, B. M. Rein, and B. C. Chung, *J. Amer. Chem. Soc.*, 86, 964 (1964); (e) S. Weinstein and H. J. Lucas, *ibid.*, 61, 1576, 2845 (1939).

2,3-Dibromobutane. (−)-(2*R*)-Butanol is obtained from the lithium aluminum hydride reduction of (+)-2,3-epoxybutane; the epoxide then must have been (2*R*,3*R*).

Treatment of the epoxide with aqueous HBr (48%) gave bromohydrin in 71% yield. Cleavage of the epoxide with HBr occurs by backside attack by the bromide ion;[29e] the chirality of the carbon that bears the bromine atom is inverted. Consequently, this bromohydrin must be (+)-(3*R*)-bromobutan-(2*S*)-ol (*erythro*).

When (+)-*erythro*-bromohydrin was treated with triphenylphosphine and bromine, a mixture of *meso*- and the dissymmetric 2,3-dibromobutane was obtained. The dissymmetric 2,3-dibromobutane was levorotatory. The product which is optically active must arise from backside attack by bromide ion on the organophosphorus intermediate (Scheme VII). Note that the reaction proceeding through the *trans*-bromonium ion (or any other frontside displacement) can produce only the *meso* diastereomer; also, only *d,l* material can arise from the equilibration of *meso*. If there is a pathway to a *cis*-bromonium ion, this intermediate cannot lead to active products.

Since 2*S*,3*S* must necessarily be the configuration of the 2,3-dibromobutane produced by backside displacement, the observed negative rotation of the product offers unequivocal proof that the sign of rotation of (2*S*,3*S*)-dibromobutane is negative. The optical rotation of the dibromide obtained from this reaction scheme is $[\alpha]_D$ −6.56°, $[\alpha]_{365}$ −21.0°, which corresponds to 21.4% optical purity (*vide infra*). Since optically pure epoxybutane was used, extensive racemization probably occurred upon treatment of the bromohydrin with $(C_6H_5)_3PBr_2$. The racemization could have occurred either by bromide ion equilibration of the 2,3-dibromobutanes or by elimination to form olefins and subsequent addition of bromine.

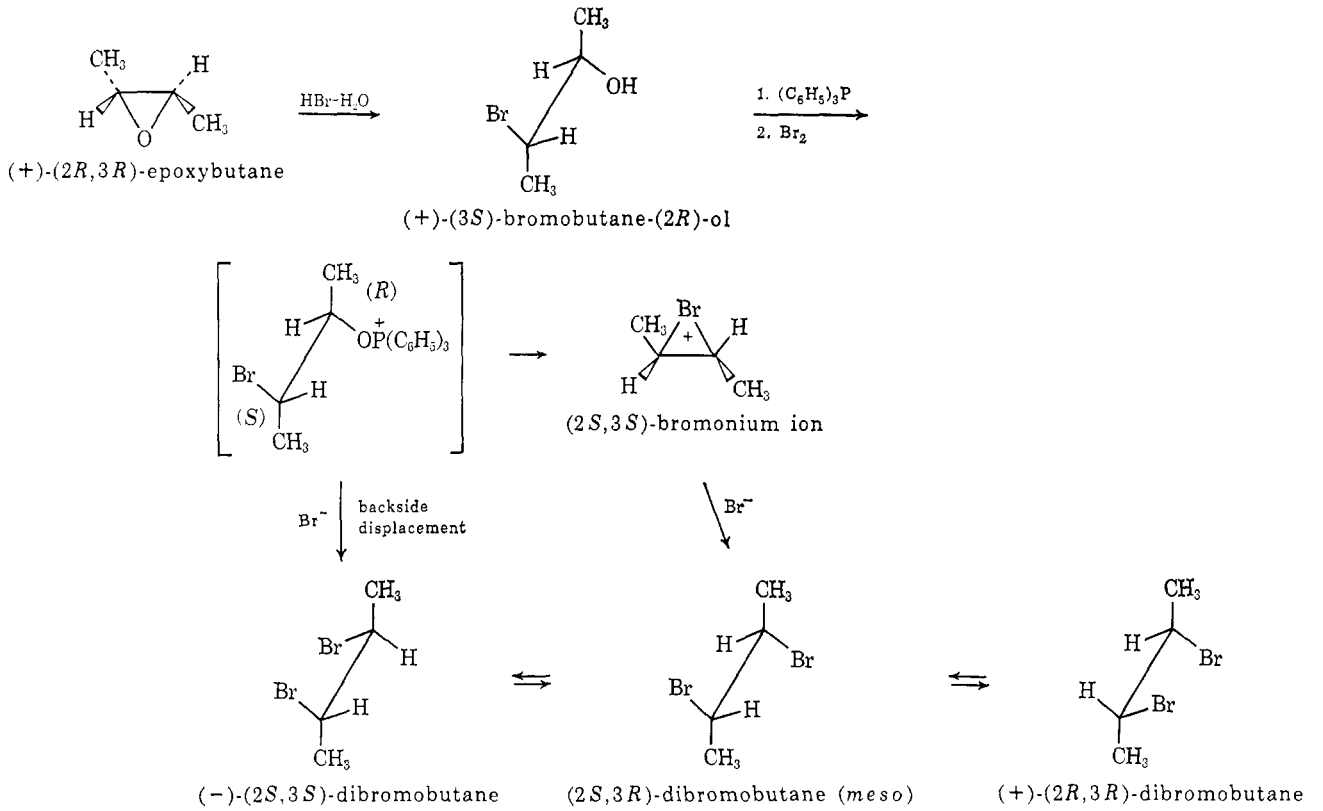
The partial resolution of *d,l*-2,3-dibromobutane with brucine has been described,[30] resulting in $[\alpha]_D$ 2.5°. Contrary to the earlier statements, this separation does not depend on preferential destruction of one of the enantiomers. Preferential entrapment of the (+)-dibromide in the brucine crystals is the basis of the separation. After digestion of 0.5 mol of brucine in 1.0 mol of *d,l*-2,3-dibromobutane, approximately 65% of the dibromide can be pumped off, α_D −8.7°; treatment of the solid with aqueous acid releases the remainder, α_D +18°. Three repetitions of this procedure produced a sample with α_D +47.3°, α_{365} +127°, $[\alpha]_{365}$ +71°.

Examination of samples of different degrees of resolution by differential scanning calorimetry[31] showed that on rapid cooling of the melt two different phase systems were obtained at random, one a simple eutectic system, the other with racemate compound formation. Heats of fusion of all forms were 2.8 ± 0.1 kcal/mol. Analysis of two of the samples gave independent values of the enantiomeric purity. A sample, α_{365} −39.4°, crystallizing the racemate compound (mp −37°), yielded data which, on curve-shape analysis, showed the sample to be 22.4% resolved; this indicates for the pure enantio-

(30) (a) H. J. Lucas and C. W. Gould, Jr., *J. Amer. Chem. Soc.*, 64, 602 (1942); (b) S. Winstein and R. E. Buckles, *ibid.*, 64, 2782 (1942).

(31) C. Fouquey and J. Jacques, *Tetrahedron*, 23, 4009 (1967).

Scheme VII



mer $[\alpha]_{365}$ −98°. Another sample, α_{365} +121.4°, crystallizing in the simple eutectic system showed it was 34% *d,l*, thus giving a value of $[\alpha]_{365}$ +103° for the pure enantiomer. Despite this good agreement the values proposed for the pure enantiomer are $[\alpha]^{20}{}_{365}$ 100° and $[\alpha]^{20}D$ 36.8°, with an error limit of 10%.

erythro-**2-Bromo-3-chlorobutane** was subjected to nine brucination cycles giving finally a sample with $[\alpha]^{28}{}_{546}$ −4.76°; this is a very low value compared with that obtained above. Since the absolute configuration of the erythro diastereomer is *meso*-like, *R,S*, a much lower absolute rotation than that of the threo diastereomer, or the *d*- or *l*-2,3-dibromobutane is to be anticipated. Unfortunately, differential scanning calorimetry was not successful in establishing the enantiomeric purity of this sample because of unsatisfactory crystallization properties. However, values are obtained for the pure enantiomer if the kinetic arguments (*vide supra*) are accepted: from the chlorination of 2-bromobutane, $[\alpha]^{25}{}_{546}$ +7.8°; from the bromination of 2-chlorobutane, $[\alpha]^{24}{}_{546}$ −10 ± 3°. Since both of these reactions proceed with retention of configuration at the original C–X site, the assignment follows: (−)-(2*R*)-bromo-(3*S*)-chlorobutane and (+)-(2*S*)-bromo-(3*R*)-chlorobutane.

threo-**2-Bromo-3-chlorobutane** was subjected to four brucination cycles. The recovered bromochloride had $[\alpha]^{28}{}_{546}$ −13°. Differential scanning calorimetry showed this sample to be 32.5% optically pure, thus $[\alpha]^{28}{}_{546}$ is −40° for the pure enantiomer.

3-Bromo-1-chlorobutane is the product of chlorination of (+)-(2*S*)-bromobutane, and therefore must be (+)-(3*S*)-bromo-1-chlorobutane, of the same configuration and optical purity. Therefore, for the pure enantiomer, $[\alpha]^{25}{}_{546}$ is +38.5°.

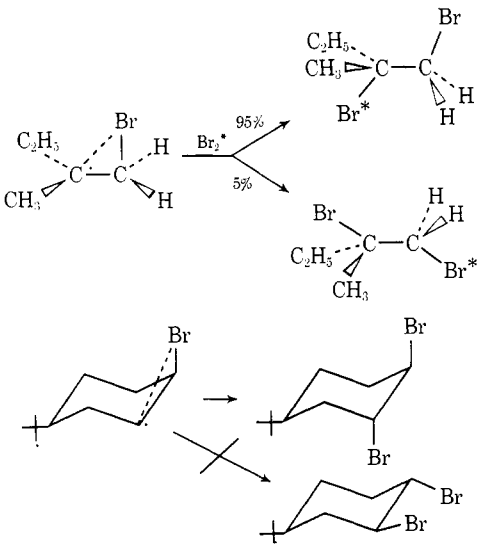
1-Bromo-2-chlorobutane is a rearrangement product obtained in the chlorination of 2-bromobutanes. If the proposed mechanism is accepted, it should have the same optical purity as the starting material and opposite configuration: (−)-1-bromo-(2*R*)-chlorobutane, $[\alpha]^{25}{}_{546}$ −34.5°.

Conclusions

In free-radical brominations of 2-bromobutanes, the product stereochemistry is determined in the rate limiting hydrogen abstraction step. The finding is in accordance with the hypothesis of a bromine assisted hydrogen atom abstraction step to produce stereospecifically two bridged radicals, one cis, the other trans.

These 2,3-bromobutyl radical intermediates are "kinetically symmetrical." It is not yet known with certainty whether a static, symmetrically bridged or a pair of unsymmetrically bridged rapidly equilibrating ($\tau_{1/2}$ ~10^{-11} sec) intermediates is responsible for these results. However, in instances where there are structural asymmetries the bridged radicals show characteristics of unsymmetrical bridging. For example, (1) the bridged radical obtained in photobromination of 1-bromo-2-methylbutane reacts with Br_2 almost exclusively at C-2,[32] (2) the photobromination of *cis*-4-bromo-1-*tert*-butylcyclohexane proceeds through a bridged intermediate which reacts asymmetrically,[9] (3) the chlorination at the primary positions of isopropyl,[9] *sec*-butyl, and *tert*-butyl[9] bromides with *tert*-butyl hypochlorite take place with 100% rearrangement of the bromine to the primary position. Consequently, it is probable that also in cases of structural symmetry, such as 2,3-bromobutyl radical, a double potential energy minimum describes the system, as in the case of

(32) D. C. Lewis and P. S. Skell, unpublished results.



the 2,3-chlorobutyl radical. The kinetic requirement of a 10^{11}-sec^{-1} interconverson rate for the 2,3-bromobutyl is explainable with a barrier of 2–4 kcal/mol separating the two minima.

The 2,3-chlorobutyl radical is best described as an unsymmetrically bridged intermediate with the chlorine atom remaining more strongly associated with its original carbon for $>10^{-9}$ sec. The barrier separating the double minimum in the 2,3-chlorobutyl radical system is more than 3 kcal/mol larger than the barrier for the corresponding bromo radical.

Experimental Section

General. All nmr spectra were obtained with a Varian A-60-A or HA-100 spectrometer. Chemical shifts are reported as τ values measured from TMS as internal standard. Vpc analyses were carried out on Nittany Scientific or F&M (thermal conductivity detector) or Perkin-Elmer F-11 (flame ionization detector) instruments.

Two columns were used extensively throughout the work: column A, 6 ft × 0.25 in. diisodecyl phthalate (10%) on Gas Chromosorb R; column B, 16 ft × 0.25 in. Carbowax 1000 (20%) on Gas Chromosorb A.

Optical rotations were obtained on a Rudolph Model 200 photoelectric polarimeter or a Perkin-Elmer F-22 spectropolarimeter.

Light sources were ordinary tungsten filament frosted light bulbs (50–500 W).

A Nittany Scientific thermal conductivity detector gas chromatograph coupled with a Cary 5010 ion chamber oven was used to determine consecutively the relative abundance and radioactivity of reaction products.

Materials. Methylene chloride, trichlorofluoromethane, and carbon tetrachloride were distilled prior to use. 2-Bromobutane, 2-chlorobutane, and NBS were obtained commercially and used without further purification.

Optically Active 2-Halobutanes. (−)-2-Butanol was prepared by the lithium aluminum hydride reduction of (+)-2,3-epoxybutane.[33,34]

(+)-2-Bromobutane was prepared from (−)-2-butanol by reaction with triphenylphosphine dibromide or with PBr_3.[29b] Both reactions yield product with inverted configuration.

(+)-2-Chlorobutane was prepared from (−)-2-butanol by the procedure of Goodwin and Hudson using chlorodiphenylphosphine.[29b] The recovered chloride (56%) was purified by washing with cold syrupy phosphoric acid and then distillation.

***threo*- and *erythro*-3-Deuterio-2-bromobutane.**[35] Deuterium bromide (60 mmol, prepared by the reaction of D_2O with PBr_3) and *cis*-2-butene (45 mmol) were condensed into an evacuated quartz flask at liquid nitrogen temperature. After degassing by two freeze–thaw cycles the mixture was warmed to −107° and irradiated with a Hanovia medium-pressure mercury lamp until no further DBr was taken up (measured manometrically). The mixture was distilled through a −107° trap on a vacuum line to remove excess deuterium bromide. The liquid remaining in the −107° trap was washed (aqueous K_2CO_3), then distilled yielding 4.5 g (74%) of *erythro*-3-deuterio-2-bromobutane, bp 91°.

The threo diastereomer was prepared similarly in 87% yield from *trans*-2-butene.

Isotopic and stereochemical purity of products were determined by a dehydrohalogenation scheme. Base dehydrohalogenation (*t*-BuOK, DMSO) gives a quantitative yield of butenes (1-butene, *trans*-2-butene, and *cis*-2-butene).[36] Their composition was checked by glc (column A). The individual butenes were analyzed by mass spectrometry (10.5 eV) for deuterium content.

The composition of the butene samples can be used to determine the per cent of undeuterated and diastereomeric impurities in the *threo*- and *erythro*-3-deuterio-2-bromobutanes samples. Assuming the dehydrohalogenation reactions proceed quantitatively with trans stereospecificity,[35] a pure erythro sample should produce *trans*-2-butene-d_0 and *cis*-2-butene-d_1. Similarly, a pure threo sample should produce *trans*-2-butene-d_1 and *cis*-2-butene-d_0.

Since *cis*-2-butene-d_1 should be produced only from the dehydrohalogenation of *erythro*-3-deuterio-2-bromobutane, any present in the threo sample must be due to erythro impurity. After subtraction of the erythro contribution, the residual *trans*-2-butene-d_0 must arise from undeuterated 2-bromobutane.[37] The results of these calculations are given in Table V.

Table V. Per Cent Purity of Diastereomeric 3-Deuterio-2-bromobutanes

	threo-3-Deuterio	*erythro*-3-Deuterio	2-Bromobutane
Threo	88.6	5.7	5.7
Erythro	2.3	92.3	5.4

1-Bromo-2-chlorobutane. A 60:40 mixture of 1-bromo-2-chlorobutane and 1-chloro-2-bromobutane was obtained by the BrCl addition to 1-butene. The products could be separated on column B. Identification of 1-chloro-2-bromobutane was obtained by adding gaseous HBr to 1-chloro-2-butene[38] followed by comparison of glc retention times with the BrCl addition to 1-butene (Chart I). All of the isomeric C_4 bromochlorides could be separated on column B. A summary of their glc retention times is found in Chart I. The relative yields are indicated by lengths of the lines.

***erythro*-2-Bromo-3-chlorobutane** was obtained as the major product from the BrCl addition to *trans*-2-butene: bp 50–52° (51 mm); nmr (CCl_4) τ 5.81 (m, 2 H), 8.21 (d, J = 6 Hz), 8.35 (d, J = 6.2 Hz), the latter two totaling 6 H.

A 90-g sample of I was subjected to seven brucinations, giving finally a 1.0-g sample with $[\alpha]^{28}_{546}$ −4.76°; the rotation increased steadily by about 0.6°/resolution.

***threo*-2-Bromo-3-chlorobutane** was prepared from the BrCl addition to *cis*-2-butene: bp 50–52° (30 mm); nmr (CCl_4) τ 5.89 (m, 2 H), 8.25 (d, J = 6.5 Hz), 8.386 (d, J = 6.5 Hz), the latter two totaling 6 H. A sample of the above was partially resolved by four brucination cycles to give *threo*-2-bromo-3-chlorobutane, $[\alpha]^{28}_{546}$ −13.0°. Further resolution of this sample was not attempted. Differential scanning calorimetry indicated the absolute rotation for the pure enantiomer is $[\alpha]^{28}_{546}$ −40°.

2-Bromo-2-chlorobutane, the major product from the photobromination of 2-chlorobutane, has the following spectral prop-

(33) P. J. Leroux and H. J. Lucas, *J. Amer. Chem. Soc.*, **73**, 41 (1951).

(34) We gratefully acknowledge a generous gift of (+)-2,3-epoxybutane from Professor G. K. Helmkamp, University of California, Riverside.

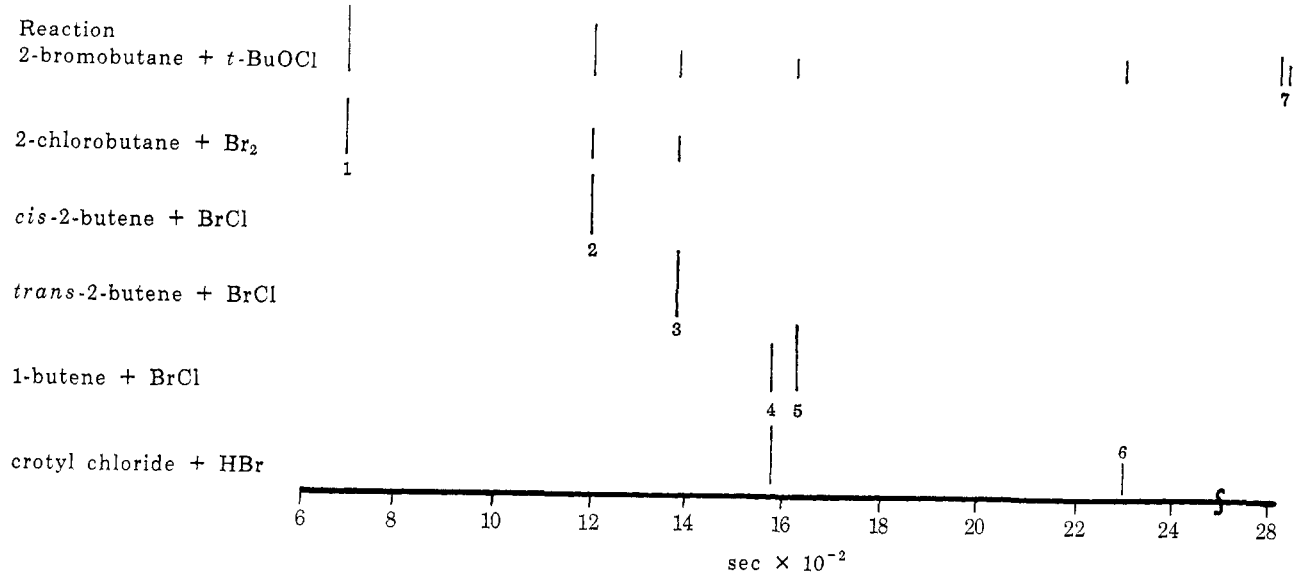
(35) (a) P. S. Skell and R. G. Allen, *J. Amer. Chem. Soc.*, **81**, 5383 (1959); (b) P. S. Skell, R. G. Allen, and G. K. Helmkamp, *ibid.*, **82**, 410 (1960); (c) P. S. Skell and W. L. Hall, *ibid.*, **85**, 2851 (1963).

(36) Butene isomerization was not found to be important under the dehydrohalogenation condition. When 5-mmol samples of *cis*- and *trans*-2-butene and 1-butene were treated individually with DMSO (1.5 ml) and *t*-BuOK (100 mg) at 20° for 20 min, the 2-butenes were recovered unchanged (<1% isomerization) and the 1-butene sample contained 18% *cis*-2-butene and 0.5% *trans*-2-butene.

(37) Details of this analysis are found in the Ph.D. Thesis of R. R. Pavlis, The Pennsylvania State University, 1969.

(38) 1-Chloro-2-bromobutane and 1-chloro-3-bromobutane had been identified previously: M. S. Kharasch, W. S. Zimmt, and W. Nudenburg, *J. Org. Chem.*, **20**, 1430 (1955).

Chart I. Glc Retention Times on Column B



1. 2-bromo-2-chlorobutane
2. *erythro*-2-bromo-3-chlorobutane
3. *threo*-2-bromo-3-chlorobutane
4. 1-chloro-2-bromobutane
5. 1-bromo-2-chlorobutane
6. 1-chloro-3-bromobutane
7. C_4 dichlorobromides

erties: nmr (CCl_4) τ 8.75 (t, J = 7 Hz, 3 H), [7.62 (s), 7.65 (q, J = 7 Hz), 5 H]; ms (70 eV) 174, 172, 170 (M^+), 159, 157, 155, 145, 143, 141, 137, 136, 135, 134, 109, 107, 105, 93, 91 (base), 55 (base).

Photochlorination of (+)-2-Bromobutane with *tert*-Butyl Hypochlorite. A degassed solution of (+)-2-bromobutane, $[\alpha]^{25}_{546}$ +16.1° (23 mmol), and *tert*-butyl hypochlorite (23 mmol) in trichlorofluoromethane (5 ml) was irradiated at −78° with a 500-W tungsten filament lamp (2 in.) for 17 hr. The solution was diluted with pentane (7 ml) and washed with H_3PO_4, Na_2CO_3, and water until neutral to litmus, then dried ($MgSO_4$). Products were separated by preparative glc (column B) and their rotations determined as solutions in 1-bromobutane solvent. Product identification was based upon a combination of glc retention times (see Chart I), and spectral properties of samples isolated by preparative glc. The product yields are given in Table III.

Photobromination of (+)-2-Chlorobutane. A stirred solution of (+)-2-chlorobutane $\alpha^{24}D$ +31.1° (54 mmol), NBS (25 mmol), and bromine (5 mmol, $[Br_2]$ = 0.1 M), in methylene chloride (50 ml) in a Pyrex flask was irradiated under a nitrogen atmosphere with a 300-W tungsten filament lamp (2 in.) for 25 min. The temperature of the reaction mixture remained at *ca.* 42°. The resulting solution was washed with bisulfite, water, $NaHCO_3$, and H_2O and then dried (Na_2SO_4). After concentration by distillation, the products were separated by preparative glc (column A). The yields and rotations of recovered products are given in Table IV.

Bromination of (+)-2-Bromobutane. A mixture containing NBS (3.7 mmol), (+)-2-bromobutane (α_{365} +115.7°, 71% optical purity, 3.6 mmol), and bromine (3.5 mmol) in sufficient trichlorofluoromethane to make 3-ml solution volume, was irradiated at 18° for 7 hr (500-W tungsten filament bulb). Excess bromine and NBS were removed by washing with $NaHSO_3$. The products and their molar percentages, as indicated by glc, were as follows: (+)-2-bromobutane (88.6%), 2,2-dibromobutane (1.1%), *meso*-2,3-dibromobutane (7.2%), *d,l*-2,3-dibromobutane (3.0%). Starting material and *d,l*-2,3-dibromobutane were recovered by preparative glc (column B). Their optical rotations are given in the text. The product distributions and optical activity are insensitive to a 125-fold change in bromine concentration (0.01–1.25 M Br_2) and a change in conversion from 10 to 30%.

Partial Resolution of *d,l*-2,3-Dibromobutane. To *d,l*-2,3-dibromobutane (28.7 g, 0.14 mol) was added brucine (19 g, 41 mmol). The resulting thick paste was allowed to stand for 3 hr. Part of the 2,3-dibromobutane was pumped off under vacuum; in 16 hr, 18.7 g had distilled, α_{365} −23.6°. The brucine and 2,3-dibromobutane residue were dissolved in 10% H_2SO_4 and extracted with ether. Vacuum trap to trap distillation gave recovered dibromobutane, α_{365} +48.7°, 7.4 g.

The procedure was repeated twice on the dextrorotatory material yielding 0.34 g of 2,3-dibromobutane, α_{365} +122.1° or $[\alpha]_{365}$ +72°. Differential scanning calorimetry of this sample indicated it to be 65.4% optically pure, thus with α_{365} +185° or $[\alpha]_{365}$ +102°.

Attempted Isomerization of *d,l*-2,3-Dibromobutane. Pure samples of *d,l*-2,3-dibromobutane were subjected to photobromination conditions. After 4 hr of irradiation *meso*-2,3-dibromobutane was not detected.

Photobromination of *threo*- and *erythro*-3-Deuterio-2-bromobutanes. *erythro*- or *threo*-3-deuterio-2-bromobutane (10 mmol), NBS (10.0 mmol), and bromine (9.4 mmol) were dissolved in 5 ml of $CFCl_3$. The mixture was degassed and irradiated with stirring for 6 hr at 15° (500-W bulb, 10 cm). The mixture was then washed with $NaHSO_3$ solution, then distilled through a 20-cm column to remove $CFCl_3$. The residue was analyzed by glc. *meso*- and *d,l*-2,3-dibromobutane were collected by preparative glc (column B) and analyzed by mass spectrometry. Unreacted starting material was subjected to the analysis scheme described previously and was found to be largely unchanged (15.7% threo, 81.7% erythro, 2.6% d_0 and 85.0% threo, 9.7% erythro, 5.3% d_0). The isomer distributions of product *meso*- and *d,l*-2,3-dibromobutane were corrected for undeuterated and isomer impurities. The results of these photobrominations are given in the text.

Synthesis of Radioactive 3-Bromopentane. Elemental bromine (6 mg) was sealed in a break seal quartz ampoule, encapsulated in polyethylene, and irradiated in the Pennsylvania State University Triga reactor operating at 500 kW for 25 min. Short-lived radioisotopes were allowed to decay 1 day. The sample contained 162 mCi; the radioactive isotope present was ^{82}Br, half-life 35.7 hr. A solution of 3-pentanol (prepared by $NaBH_4$ reduction of 3-pentanone, uncontaminated by 2-pentanone), and triphenylphosphine (1.32 g) in HMPA (3 ml) was treated with 0.01 ml of bromine to destroy substances present in the HMPA which reacted with bromine. In a preliminary experiment failure to do this resulted in a feebly radioactive product. The reaction vessel was connected to a Hg free vacuum line, cooled to −196°, and evacuated. The quartz ampoule containing ^{82}Br was broken inside a section of this vacuum line and its contents distilled into the cold reaction mixture. The reaction mixture was allowed to warm to room temperature and 800 mg of nonradioactive bromine was added, keeping the solution near room temperature by cooling with ice during the addition. The product 3-bromopentane was pumped back into the vacuum system, yield 2.5 mmol or 50%. This was demonstrated by glc (column B) to be free of 3-pentanol and 2-bromopentane.

Bromination of 3-Bromopentane Utilizing ^{82}Br Label. To 160 mg of bromine and 2.5 mmol of *N*-bromosuccinimide in 3 ml of $CFCl_3$ was added 2.5 mmol of radioactive 3-bromopentane. The mixture was degassed and irradiated at 15–20° with a 500-W tungsten filament bulb (20 cm) for 4 hr while keeping the mixture stirred with a magnetic stirrer.

The volatile portion of the reaction mixture was pumped into a

Hg free section of a vacuum line and condensed with liquid nitrogen. Propene (2 mmol) was added to the mixture and the vacuum line trap was warmed to −78° with a Dry Ice–acetone bath. The bromine disappeared at this point.

A 10-cm Vigreux column was used to remove most of the $CFCl_3$ and propene leaving a mixture of 3-bromopentane and dibromides.

Analysis of the reaction products was obtained on the tandem gas chromatograph ion chamber using column B; the results are given in the text.

threo-2,3-Dibromopentane, obtained by preparative glc separation from the above experiment, was treated with 1 equiv of *t*-BuOK in DMSO for 5 min. The volatile products were pumped into a cold trap and reanalyzed on the glc ion chamber apparatus. Two products were obtained from the dehydrohalogenation, *trans*-2-bromo-2-pentene and *trans*-3-bromo-2-pentene with equal relative molar radioactivities. Efforts to separate the dehydrohalogenation products from *erythro*-2,3-dibromopentane were unsuccessful. Authentic samples of the 2,3-dibromopentanes were made by addition of bromine to *cis*- and *trans*-2-pentenes, respectively. Dehydrohalogenations of these authentic dibromides provided samples of the bromoolefins. The 3-bromo-2-pentenes were recognized as products from dehydrohalogenation of 3,3-dibromopentane.

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Orientation in Base-Promoted β Eliminations from 2-Alkyl Halides and *p*-Toluenesulfonates. The Role of Base Association[1]

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Abstract: Base association in solvents of low polarity, such as *tert*-butyl alcohol, exerts a profound influence upon positional and geometrical orientation in base-promoted β eliminations from 2-butyl halides and *p*-toluenesulfonates. An effect of base association provides explanation for the following anomalous reports in the literature: (1) the high proportions of 1-alkene and the low *trans*-:*cis*-2-alkene ratios found in reactions of 2-alkyl halides with alkali metal alkoxides from tertiary alcohols in the corresponding alcohols or in hydrocarbon solvents; (2) the orientation dichotomy for base-promoted eliminations from 2-alkyl halides in alcoholic solvents and in dipolar aprotic solvents; and (3) the *trans*-:*cis*-2-alkene ratios of less than unity which are observed in reactions of 2-alkyl arenesulfonates with potassium hydroxide and alkoxides in *tert*-butyl alcohol. Rationalization of the effect of base association upon orientation in eliminations from 2-alkyl halides and arenesulfonates is presented.

In recent years, numerous investigations[3,6-10] have examined the effects of leaving group, base, solvent, and 2-alkyl group upon positional and geometrical orientation[11] in base-promoted β eliminations from 2-alkyl halides and arenesulfonates. We now report an unexpected effect of base association.

Eliminations from 2-Halobutanes

The experimental results in Table I provided the initial indication of the influence of base association upon orientation in base-promoted β eliminations from 2-alkyl halides and arenesulfonates. The relative amounts of olefinic products which result from reactions of 2-bromobutane with MeOK–MeOH, EtOK–EtOH, and *t*-BuOK–DMSO are insensitive to changes

Table I. Olefinic Products from Reactions of 2-Bromobutane with Potassium Alkoxides in Various Solvents at 50.0°

Base–solvent	[Base], *M*	[2-BuBr], *M*	% of 1-butene of total butenes	*trans*-2-Butene: *cis*-2-butene
MeOK–MeOH[a]	0.25	0.10	15.4[b]	3.34
MeOK–MeOH[a]	0.50	0.10	15.4	3.34
MeOK–MeOH[a]	1.00	0.10	15.4	3.41
EtOK–EtOH[a]	0.25	0.10	17.9	3.23
EtOK–EtOH[a]	0.50	0.10	17.9	3.21
EtOK–EtOH[a]	1.00	0.10	18.1	3.22
t-BuOK–*t*-BuOH[a,c]	0.10	0.10	37.7	1.86
t-BuOK–*t*-BuOH[a,c]	0.25	0.10	41.6	1.78
t-BuOK–*t*-BuOH[a,c]	0.50	0.10	44.1	1.66
t-BuOK–*t*-BuOH[a,c]	1.00	0.10	50.6	1.47
t-BuOK–*t*-BuOH[a]	1.00	0.25	49.8	1.47
t-BuOK–*t*-BuOH[a]	1.00	0.51	49.9	1.48
t-BuOK–DMSO[d]	0.10	0.09	30.5	3.04
t-BuOK–DMSO[d]	0.25	0.09	30.3	3.12
t-BuOK–DMSO[d]	0.50	0.09	30.6	3.16
t-BuOK–DMSO[d]	1.03	0.09	30.5	2.99

[a] Ampoule technique: R. A. Bartsch, *J. Org. Chem.*, **35**, 1334 (1970). [b] Maximum standard deviation from repetitive analysis, ±0.5%. [c] Reference 1. [d] Nitrogen gas sweep technique: R. A. Bartsch, *J. Org. Chem.*, **35**, 1023 (1970).

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(11) Positional orientation refers to the relative proportions of 1- and 2-alkenes which are formed, whereas geometrical orientation compares the relative amounts of *trans*-2-alkene and *cis*-2-alkene which are produced.[4]