Recombination Kinetics. Mathematical modeling studies of hole–electron recombination in small semiconductor particles[57] indicate that mixed kinetic behavior will obtain when the average number of pairs per particle lies between 0.5 and about 30; recombination is approximated by simple first- or second-order rate laws when the ratios are less or greater, respectively, than this range. From 1–8 μM ^{3}ZnTPPS^{4-} are formed by the laser flash under our experimental conditions, yielding 0.5–4 μM redox product ions or 2–20 pairs per vesicle. Mixed first- and second-order kinetics might therefore arise *if* the ZnTPPS^{3-} π-cation remained associated with the vesicle surface. This latter notion seems untenable in view of the system electrostatics, however. In the absence of π-cation binding, the product pairs become statistically decorrelated, and second-order kinetics will be observed at all ion/vesicle ratios. An alternative mechanism that could introduce first-order character into the recombination kinetics comprises ZnTPPS^{3-} ion pairing with C_nMV^{2+} in an encounter complex at the vesicle interface, followed by electron exchange between the sensitizer associated C_nMV^{2+} and a neighboring C_nMV^{+} ion. In this model, the interfacial electrostatics dictate preferential approach of the trianionic π-cation to dipositive viologen; EPR spectroscopy has provided evidence consistent with rapid electron exchange between vesicle-bound $MV^{2+/+}$ ions.[58] The two kinetic models give different rate laws and can perhaps be distinguished by the study of recombination dynamics currently in progress.

Acknowledgment. J.K.H. and D.H.P.T. express gratitude to Michael Grätzel for use of his laser flash kinetic facilities at EPFL, Lausanne, Switzerland, and to Michael Grätzel and Guido Rothenberger for enlightening discussions regarding interfacial reaction mechanisms. This work also benefited from the expert technical assistance of Ken Marsh and John Hurley at SERI, Golden, Colorado. Financial support was provided by the Division of Chemical Sciences, Office of Basic Energy Sciences, U.S. Department of Energy through contracts to J.K.H. (DE-AC-06-83ER13111) and J.S.C.

(57) Rothenberger, G.; Moser, J.; Grätzel, M.; Serpone, N.; Sharma, D. K. *J. Am. Chem. Soc.* **1985**, *107*, 8054–8059.

(58) Takuma, K.; Sakamoto, T.; Matsuo, T. *Chem. Lett.* **1981**, 815–818.

Evidence for a Reversible Electrophilic Step in Olefin Bromination. The Case of Stilbenes

Giuseppe Bellucci,* Cinzia Chiappe, and Franco Marioni

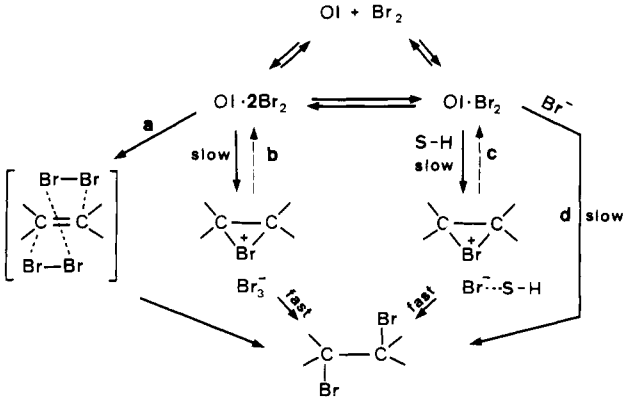
Contribution from the Istituto di Chimica Organica, Facoltà di Farmacia, Università di Pisa, 56100 Pisa, Italy. *Received June 5, 1986*

Abstract: Bromonium–bromide ion couple intermediates have been generated by reacting *erythro*- and *threo*-2-bromo-1,2-diphenylethanol with gaseous HBr in 1,2-dichloroethane and in chloroform. It has been shown that in both solvents these intermediates mainly collapse to *meso*-1,2-dibromo-1,2-diphenylethane but also release Br_2 to give *trans*-stilbene. The ratios of *trans*-stilbene to the meso dibromide obtained in all these reactions ranged between 9:91 and 22:78. The product distributions of the additions of HBr and of Br_2, both in the absence and in the presence of HBr, have also been determined. *cis*-Stilbene rapidly added HBr in both solvents, but in 1,2-dichloroethane isomerization to *trans*-stilbene also occurred to a large extent. *trans*-Stilbene mainly underwent oligo- or polymerization. The reactions of both olefins with Br_2 were found to be not stereospecific. In the presence of HBr, the bromination of *trans*-stilbene became anti stereospecific, but in the case of *cis*-stilbene it maintained only a very modest stereoselectivity, and in chloroform HBr addition was predominant. The kinetics of bromination of both *trans*- and *cis*-stilbene in 1,2-dichloroethane were shown to follow very cleanly a third-order rate law (second order in Br_2). However, the product analysis during the bromination of *cis*-stilbene showed that significant amounts of the trans olefin were always present at incomplete conversion. It has been shown that the latter olefin is formed by Br_2-catalyzed isomerization of the starting cis olefin. All these results can be rationalized by assuming that the formation of bromonium–bromide or bromonium–tribromide ion pair intermediates in the discussed reactions is actually reversible.

In spite of its intensive investigation,[1] the mechanism of olefin bromination, in appearance one of the simplest standard textbook organic reactions, is still the object of debate. The stepwise nature of the addition has been recognized for a long time, but important features of the reaction steps are continuously being brought to light.[2-5]

At least four alternative nonradical mechanistic pathways, all of which involve olefin·Br_2 charge-transfer complexes (CTCs),

Scheme I



appear to have been proved for the bromination in low polarity nonnucleophilic aprotic solvents, where the reaction is not complicated by the formation of solvent-incorporated products.

The first pathway (a in Scheme I) has been proposed for the slow brominations in apolar solvents like carbon tetrachloride[6]

(1) For extensive recent reviews of olefin brominations, see: (a) Schmid, G. H.; Garratt, D. G. *The Chemistry of Double Bonded Functional Groups*; Patai, S., Ed.; Wiley: New York, 1977; Suppl. A, Part 2, p 725. (b) V'yunov, K. A.; Ginak, A. I. *Russ. Chem. Rev. (Engl. Transl.)* **1981**, *50*, 151–163. (c) De la Mare, P. B. D.; Bolton, R. *Electrophilic Additions to Unsaturated Systems*, 2nd ed.; Elsevier: New York, 1982; pp 136–197.

(2) (a) Ruasse, M.-F.; Zhang, B.-L. *J. Org. Chem.* **1984**, *49*, 3207–3210. (b) Ruasse, M.-F.; Lefebvre, E. *J. Org. Chem.* **1984**, *49*, 3210–3212.

(3) (a) Fukuzumi, S.; Kochi, J. K. *Int. J. Chem. Kinet.* **1983**, *15*, 249–266. (b) Fukuzumi, S.; Kochi, J. K. *J. Am. Chem. Soc.* **1982**, *104*, 7599–7609. (c) Fukuzumi, S.; Kochi, J. K. *J. Am. Chem. Soc.* **1981**, *103*, 2783–2791.

(4) Brown, R. S.; Gedye, R.; Slebocka-Tilk, H.; Buschek, J. M.; Kopecky, K. R. *J. Am. Chem. Soc.* **1984**, *106*, 4515–4521.

(5) Bellucci, G.; Bianchini, R.; Ambrosetti, R. *J. Am. Chem. Soc.* **1985**, *107*, 2464–2471.

0002-7863/87/1509-0515$01.50/0

Table I. Product Yields from the Reactions of *erythro*-**1** and *threo*-**2** with Hydrogen Bromide

run	compd	solvent	time, h	yield, %[a]				
				1	**2**	**3**	**4**	**5**
1	**1**	$(CH_2Cl)_2$	1	<1		56		12
2	**1**	$CHCl_3$	1	<1		63		17.5
3[b]	**2**	$(CH_2Cl)_2$	4.5		30.5	34.5		3.5
4[c]	**2**	$CHCl_3$	4.5		67.5	7.5	4	2

[a] Average of three reactions. When carried out with similar flow rates of HBr, these yields were reproducible within ±10% of the quoted figures. [b] Only a trace (≤0.2%) of *cis*-stilbene was detected. [c] *cis*-Stilbene (~0.5%) and 1-bromo-1,2-diphenylethane (~0.5%) were also detected.

and consists of a direct rearrangement of a 1:2 olefin·Br_2 complex through a nonpolar six-membered transition state. This mechanism requires a second-order dependence on Br_2 of the bromination rate. Kinetic investigations under these conditions are however conflicting.[7]

In solvents of even very modest polarity, the 1:2 complex can instead undergo a rate-determining cleavage of a bromine–bromine bond to give a bromonium–tribromide ion pair intermediate, which then collapses rapidly to dibromide and molecular Br_2 (path b).[5,8,9] Also pathway b involves a second-order dependence on Br_2 of the rate that has been clearly demonstrated for brominations in several chlorinated hydrocarbon solvents.[8,10,11]

A similar ionic mechanism, where a solvent-assisted bromine–bromine bond breaking occurs in a 1:1 olefin·Br_2 CTC and the reaction is first-order in Br_2 (path c), has been definitely established for bromination at low Br_2 concentration in hydroxylic solvents,[12,13] which provide specific electrophilic solvation by hydrogen bonding to the leaving bromide ion.[14,15] At higher Br_2 concentration, a third-order process of type b has been reported also in acetic acid.[13b]

In the presence of added bromide salts, which in low polarity nonprotic solvents bind Br_2 as a highly stable Br_3^- ion,[16] or when preformed Br_3^- salts are used as the brominating reagent, the bromination has been shown to proceed through rate- and product-determining nucleophilic attack by Br^- on 1:1 olefin·Br_2 CTCs (path d).[8,17] A mechanism of the latter type is probably involved also in brominations carried out in the presence of basic compounds (heteroaromatic amines or ethers) able to complex bromine, as suggested by product distribution studies.[18]

Pathways a and d involve CTCs as the only reaction intermediates, formed in reversible preequilibrium steps. Pathways b and c involve instead a further discrete intermediate, a bromonium or bromocarbenium ion, depending on the olefin structure and reaction conditions, coupled to a tribromide or to a bromide ion. This intermediate, in principle, may evolve to 1,2-dibromide or revert back to CTCs and then to olefin and Br_2, depending on the relative rates of the direct and reverse reaction. The latter is, however, usually ignored in the kinetic treatments of bromination reactions, where the rate-determining step is regarded as not reversible.[1] This is indicated by dotted arrows in Scheme I.

Yet, this step is easily reversible when the collapse of the ion pair to 1,2-dibromide is prevented sterically, as in the case of the bromonium–tribromide salt formed from Br_2 and adamantylideneadamantane.[19,20] Furthermore, reversion back to olefin and molecular Br_2 has been recently reported for cyclohexene and cyclopentene bromonium ions generated solvolytically from the corresponding trans bromo brosylates in warm acetic acid containing Br^- and a scavenger olefin.[4] This result was obtained, however, under more drastic conditions than those usually employed in bromination work and the crossed bromination products were detected in rather low amounts, particularly from *trans*-2-bromocyclopentanol brosylate and cyclohexene.

It occurred to us that bromonium–bromide-type intermediates similar to those involved in brominations may be most simply generated by reacting appropriate bromohydrins with hydrogen bromide in nonprotic low polarity solvents. Since Br_2 can be stripped from these solvents by a vigorous stream of the gaseous hydrogen halide,[21] the above reaction appeared particularly suitable to test the reversibility of the ion pair intermediates to Br_2 and olefin under mild conditions similar to those employed in typical bromination. The diastereomeric *erythro*- and *threo*-2-bromo-1,2-diphenylethanols were chosen for this investigation because occasional literature reports[22,23] on the isomerization of *cis*- to *trans*-stilbene during bromination suggested[24] a reversible formation of ionic intermediates capable of rotation about the C–C bond.[25] In order to check the occurrence and the kinetic im-

(6) Sergeev, G. B.; Serguchev, Yu. A.; Smirnov, V. V. *Russ. Chem. Rev. (Engl. Transl.)* **1973**, *42*(9), 697–712. Sergeev, G. B.; Ch'êng T'ung-Ha; Pokholok, T. V. *Kinet. Katal.* **1969**, *10*, 47–51.

(7) Olefin bromination in carbon tetrachloride has been reported as a second-order process (Hanna, J. G.; Siggia, S. *Anal. Chem.* **1965**, *37*, 690–692. Garnier, F.; Dubois, J.-E. *Bull. Soc. Chim.* **1968**, 3797–3803) or a third-order process (Buckles, R. E.; Miller, J. L.; Thurmaier, R. J. *J. Org. Chem.* **1967**, *32*, 888–892. Gebelein, C. G.; Frederick, G. D. *J. Org. Chem.* **1972**, *37*, 2211–2217. Sergeev, G. B.; Smirnov, V. V.; Bakarinova, G. A.; Vetrova, M. A. *Dokl. Akad. Nauk SSSR* **1972**, *203*, 394–397. Shilov, E. A.; Sergeev, G. B.; Serguchev, Yu. A.; Smirnov, V. V. *Ukr. Khim. Zh.* **1972**, *38*, 1156–1162) and as a mixed second-order and third-order process (ref 3 and: Schmid, G. H.; Toyonaga, B. *J. Org. Chem.* **1984**, *49*, 761–763). Unreproducible bromination rates have been reported and ascribed to the presence of small amounts of water and of HBr formed by side reactions in CCl_4, where reproducible third-order rate constants were however obtained after addition of *N*-bromoamides as HBr scavengers (Byrnell, C. J. A.; Coombes, R. G.; Hart, L. S.; Whiting, M. C. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1079–1086). Different mechanistic interpretations have also been given for the third-order term observed in CCl_4 (see, for instance, ref 3a, 6, and 37).

(8) (a) Bellucci, G.; Bianchini, R.; Ambrosetti, R.; Ingrosso, G. *J. Org. Chem.* **1985**, *50*, 3313–3318. (b) Bellucci, G.; Bianchini, R.; Vecchiani, S. *J. Org. Chem.*, in press.

(9) It has been recognized (ref 3a, footnotes 11 and 12) that the charge-transfer formulation proposed for the slow step of both the second-order and the third-order bromination processes is not to be distinguished in detail from the more commonly accepted ones shown in paths b and c of Scheme I. In fact, the collapse of the charge-transfer ion pair [C^+–C^+ Br_2^-] to products can be visualized as occurring through a second, bromonium bromide ion pair, whose involvement in the product-determining transition state is shown by product studies (see, for instance, the discussions in ref 8b and 18b,c).

(10) Modro, A.; Schmid, G. H.; Yates, K. *J. Org. Chem.* **1977**, *42*, 3673–3676.

(11) De la Mare, P. B. D.; Wilson, R. D. *J. Chem. Soc., Perkin Trans. 2* **1977**, 2048–2054.

(12) (a) Dubois, J.-E.; Mouvier, G. *Tetrahedron Lett.* **1963**, 1325–1331. (b) Dubois, J.-E.; Mouvier, G. *Bull. Soc. Chim.* **1968**, 1426–1435.

(13) (a) Rolston, J. H.; Yates, K. *J. Am. Chem. Soc.* **1969**, *91*, 1483–1491. (b) Yates, K.; Mc Donald, R. S.; Shapiro, S. A. *J. Org. Chem.* **1973**, *38*, 2460–2464.

(14) Garnier, F.; Donnay, R. H.; Dubois, J.-E. *Chem. Commun.* **1971**, 829–830.

(15) Modro, A.; Schmid, G. H.; Yates, K. *J. Org. Chem.* **1979**, *44*, 4221–4224.

(16) Bellucci, G.; Berti, G.; Bianchini, R.; Ingrosso, G.; Ambrosetti, R. *J. Am. Chem. Soc.* **1980**, *102*, 7480–7486.

(17) Bellucci, G.; Berti, G.; Bianchini, R.; Ingrosso, G.; Yates, K. *J. Org. Chem.* **1981**, *46*, 2315–2323.

(18) (a) Barili, P. L.; Bellucci, G.; Marioni, F.; Morelli, I.; Scartoni, V. *J. Org. Chem.* **1972**, *37*, 4353–4357. (b) Bellucci, G.; Ingrosso, G.; Marioni, F.; Mastrorilli, E.; Morelli, I. *J. Org. Chem.* **1974**, *39*, 2562–2565. (c) Barili, P. L.; Bellucci, G.; Marioni, F.; Scartoni, V. *J. Org. Chem.* **1975**, *40*, 3331–3337. (d) Barili, P. L.; Bellucci, G.; Marioni, F.; Morelli, I.; Scartoni, V. *J. Org. Chem.* **1973**, *38*, 3472–3478.

(19) Strating, J.; Wieringa, J. H.; Wynberg, H. *Chem. Commun.* **1969**, 907–908.

(20) Slebocka-Tilk, H.; Ball, R. G.; Brown, R. S. *J. Am. Chem. Soc.* **1985**, *107*, 4504–4508.

(21) Bromine is completely removed from a 10^{-3} M solution in 1,2-dichloroethane by bubbling a vigorous stream of HBr within 5 min.

(22) Buckles, R. E.; Bader, J. M.; Thurmaier, R. J. *J. Org. Chem.* **1962**, *27*, 4523–4527.

(23) Yates, K.; Mc Donald, R. S. *J. Org. Chem.* **1973**, *38*, 2465–2478.

(24) See ref 1c, p 158.

(25) No detailed investigation of the type discussed in this paper, pointing to exlude other possible isomerization mechanisms, had however been carried out.

Table II. Product Yields from the Reactions of *trans*-Stilbene (**5**) and *cis*-Stilbene (**6**) with Hydrogen Bromide

run	compd	solvent	time, h	yields %[a] 5	6	7
1	**5**	$(CH_2Cl)_2$	1	38		5
2	**5**	$(CH_2Cl)_2$	2	26		8
3	**5**	$CHCl_3$	1	70		3
4	**5**	$CHCl_3$	2	40		7
5	**6**	$(CH_2Cl)_2$	1	20	<1	34
6	**6**	$(CH_2Cl)_2$	2	18	<1	38
7	**6**	$CHCl_3$	1	7	<1	52
8	**6**	$CHCl_3$	2	4	<1	58

[a] Determined in a single experiment. Errors are ±2% of the quoted figures greater than 10 and ±10% of the quoted figures less than 10. In different experiments, the yields of recovered **5** changed up to 30% of the quoted figures in runs 1–4, where oligo- and/or polymerization of the olefin was the main reaction, and about 10% in runs 5–8; the yields of **7** ranged between ±20% of the quoted figures in runs 1–4 and between ±10% of the reported figures in runs 5–8.

portance of the reverse reaction in the bromine addition, the kinetics and product distribution of bromination of both *trans*- and *cis*-stilbene in 1,2-dichloroethane have also been reinvestigated.

Results

Both the erythro and threo bromohydrins **1** and **2** were reacted with gaseous HBr in two nonprotic solvents of somewhat different polarity, 1,2-dichloroethane ($\epsilon = 10.7$) and chloroform ($\epsilon = 4.6$),[8] under identical conditions, by bubbling a vigorous gas stream through the solutions during the entire course of the reaction. The resulting mixtures were then analyzed by HPLC and the yields evaluated with respect to an added standard. The results are reported in Table I.

The two bromohydrins reacted with the hydrogen halide at very different rates: while only traces of the residual erythro bromohydrin (**1**) were detected after 1 h of reaction, large amounts of the unreacted threo diastereomer (**2**) were found even after 4.5 h (runs 3 and 4), especially when the reaction was carried out in the less polar chloroform solvent. This showed that the reaction rate was affected both by the configuration and by the solvent polarity, a more polar solvent causing an increase in rate, as expected for reactions leading to ionic intermediates.

Substantial amounts of *trans*-stilbene (**5**) were formed from the erythro bromohydrin (**1**) in both solvents. Low but accurately measurable amounts of the same olefin (**5**) were detected in the reactions of the threo diastereomer (**2**), where the conversions were far from complete. The ratio of *trans*-stilbene (**5**) to the meso dibromide (**3**) was, however, not very different in the latter (9:91 and 21:79, respectively, in runs 3 and 4) and in the former reactions (18:82 and 22:78, respectively, in runs 1 and 2). Only traces of *cis*-stilbene were detected in the reactions of **2**. The dibromide product consisted only of the meso form (**3**) in all reactions, except for that of the threo bromohydrin (**2**) in chloroform (run 4), where the meso and *d,l* dibromides **3** and **4** were formed in an about 65:35 ratio. It was independently shown that the single dibromides were quantitatively recovered unchanged after treatment with HBr under the conditions of runs 1–4. This

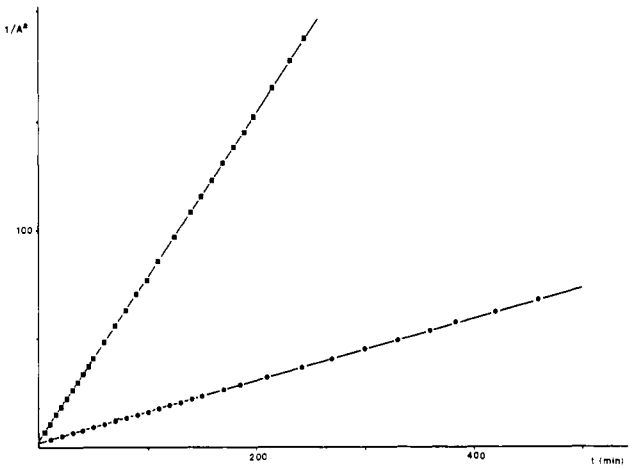


Figure 1. Third-order plots for the reactions of 2.5×10^{-3} M bromine with 2.5×10^{-3} M *trans*-stilbene (●) and *cis*-stilbene (■) in 1,2-dichloroethane at 25 °C.

excluded both the formation of *trans*-stilbene by HBr-catalyzed debromination of dibromides **3** and **4** and the interconversion of the two dibromides.

Overall yields of detected products were about 80% for the reactions carried out in chloroform (runs 2 and 4) and about 70% for those in 1,2-dichloroethane (runs 1 and 3). Since the recovery of the single products was shown by blank experiments to be >95% for all formed compounds, the missing amounts could not be due to losses during the workup and are probably attributable to the formation of undetected byproducts (see below), more abundant in the reactions performed in the more polar 1,2-dichloroethane solvent where the reactions were faster.

trans-Stilbene, having been detected as one of the primary products of the reactions of *erythro*- and *threo*-2-bromo-1,2-diphenylethanol with HBr, reactivity toward this hydrogen halide, as well as toward the Br_2 released in these reactions, was examined next in order to evaluate the actual extent of its involvement in the overall reaction.

The reactions of both stilbenes with HBr in the two solvents gave only moderately reproducible results. Table II shows the amounts of *trans*- and *cis*-stilbene (**5** and **6**) and of the HBr addition product, 1-bromo-1,2-diphenylethane (**7**), detected by HPLC in HBr-saturated 1,2-dichloroethane and chloroform solutions at different times in typical experiments. Even if somewhat different yields were obtained in duplicate runs, the same trends were always observed. *cis*-Stilbene (**6**) added HBr more rapidly than the trans isomer (**5**) both in 1,2-dichloroethane and chloroform, the reaction being nearly completed within 1 h. In the former solvent the addition was accompanied by a larger amount of isomerization to the more stable trans olefin (**5**). In both solvents *trans*-stilbene (**5**) gave always less than 10% of the HBr addition product (**7**) even after 2 h. Substantial amounts of oligomers and/or polymers were also formed from both olefins, as shown by the appearance of broad peaks with long retention times in the chromatograms. Acid-catalyzed oligomerization of stilbenes is known.[26] Similar side reactions may also account

Table III. Product Yields from the Addition of Bromine to *trans*-Stilbene (**5**) and *cis*-Stilbene (**6**) in the Absence and in the Presence of Hydrogen Bromide

run	compd	solvent	bubbled HBr	yields, %[a] 3	4	5	7
1	**5**	$(CH_2Cl)_2$	no	65	32		
2	**5**	$CHCl_3$	no	78	20		
3	**5**	$(CH_2Cl)_2$	yes	61			6
4	**5**	$CHCl_3$	yes	63			7
5	**6**	$(CH_2Cl)_2$	no	55	42		
6	**6**	$CHCl_3$	no	38	60		
7	**6**	$(CH_2Cl)_2$	yes	25	18	0.5	10
8	**6**	$CHCl_3$	yes	0.5	6	2	75

[a] Average of three reactions. Errors are ±2% of the quoted figures for reactions of Br_2 alone. For reactions of Br_2 and HBr, carried out with similar flow rates of HBr, the yields were reproducible within ±10% of the quoted figures.

for the amounts of products lacking in the reactions reported in Table I.

Table III shows the product yields obtained in the addition of Br_2 to *trans*- and *cis*-stilbene both without and with HBr bubbled through the solutions.

The reactions of both olefins with Br_2 alone were found to be not stereospecific, each giving substantial amounts of both dibromides. However, the bromination of *trans*-stilbene (**5**) showed an anti stereoselectivity that was moderate (67%) in 1,2-dichloroethane and somewhat higher (79%) in chloroform. A 61–63% yield of meso dibromide (**3**), but not *d,l* dibromide (**4**), was obtained when the addition of Br_2 was carried out under HBr bubbling (runs 3 and 4). Only 6–7% of monobromide (**7**), arising by HBr addition, was found in these reactions, in agreement with the above observed low tendency of this olefin to add the hydrogen halide. The total yields were quantitative in the absence of HBr but decreased considerably in the presence of it, probably owing to some incursion of the above-mentioned acid-catalyzed oligo- or polymerization of the olefin.

The bromination of the cis olefin (**6**) exhibited very modest and opposite stereoselectivity in the two solvents, being 57% syn in 1,2-dichloroethane but 61% anti in the less polar chloroform. With bubbled HBr the total dibromide yield from *cis*-stilbene dropped to 6% in chloroform, where HBr addition to give 1-bromo-1,2-diphenylethane (**7**) competed favorably with bromination. The different behavior of *trans*- and *cis*-stilbene in these reactions (compare runs 4 and 8 of Table III) is consistent with the observed higher tendency of the latter to add HBr (compare runs 3 and 4 and 7 and 8 of Table II). Only 10% of the monobromide (**7**) was instead obtained from *cis*-stilbene and Br_2 with bubbled HBr in 1,2-dichloroethane (run 7 of Table III), where the total dibromide yield was 43% and the meso diastereomer (**3**) was slightly predominant. In agreement with the results shown in Table II (compare runs 5 and 6 and 7 and 8), acid-catalyzed isomerization of *cis*- to *trans*-stilbene is more important in 1,2-dichloroethane than in chloroform, and the competition of Br_2 and HBr for the latter olefin appears to favor bromination to give the meso dibromide.

In order to check the reported isomerization of *cis*- to *trans*-stilbene during the addition of bromine, the olefin and halogen in a 1:1 ratio were reacted at 2.5×10^{-3} M initial concentration in 1,2-dichloroethane at 25 °C. The reaction kinetics was followed spectrophotometrically by monitoring the disappearance of Br_2 at its absorption maximum. Meanwhile, samples were withdrawn from an identical reaction at time intervals and analyzed by HPLC. For the sake of comparison, the kinetics of bromination of *trans*-stilbene under the same conditions was also examined. Both olefins were found to obey cleanly, up to over 85% conversion (Figure 1, correlation coefficients >0.9999), the third-order rate law of eq 1, whose integrated form, for identical initial concentrations (C_0) of olefin and Br_2, is given by eq 2. The third-order rate constants respectively obtained for *cis*- and *trans*-stilbene in 1,2-dichloroethane at 25 °C were $k_{3cis} = 270 \pm 10$ and $k_{3trans} = 49.5 \pm 2.5$ M^{-2} s^{-1}, in good agreement with the previously reported values.[27] The same values were obtained when the 1,2-dichloroethane solutions were saturated with oxygen.

$$-d[Br_2]/dt = k_3[Ol][Br_2]^2 \quad (1)$$

$$1/C^2 - 1/C_0^2 = 2k_3t \quad (2)$$

The reagents' and products' concentrations found at several times during the bromination of *cis*-stilbene carried out under the same conditions of the above-mentioned kinetic runs are reported in Table IV.

trans-Stilbene (**5**) was always found, besides the cis isomer (**6**), at incomplete conversion. Its amount changed slightly during the reaction and reached a maximum at about 80% conversion. The ratio of meso (**3**) to *d,l* dibromide (**4**) had a constant value of about 56:44 during the entire course of the reaction. Furthermore, it was independently confirmed that neither the *d,l* nor the meso dibromide were isomerized to each other in the presence of bromine[28] during a time much longer than that of the analyzed bromination reaction.

It must be stressed that the results of Table IV were accurately reproduced in runs carried out in the dark and in laboratory light, as well as when the reagent solutions had been saturated with oxygen, a typical free-radical scavenger. This allowed us to reject the hypothesis that any of the *cis*- to *trans*-stilbene isomerization is actually occurring during an adventitious free-radical bromination of the olefin.

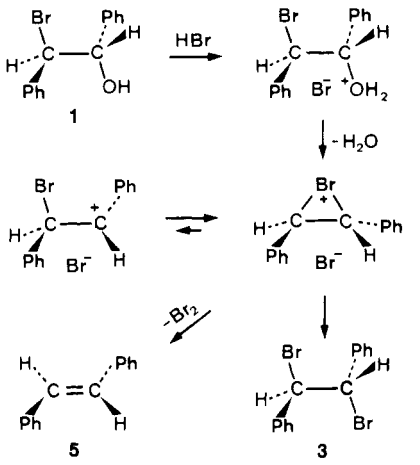
In order to exclude the formation of *trans*-stilbene from the unreacted cis isomer by the catalytic action of small amounts of HBr that could have arised from other adventitious, undetected side reactions, the cis olefin (3×10^{-3} M) was exposed to 1.5×10^{-4} M HBr in 1,2-dichloroethane for a time corresponding to three half-lives of the analyzed bromination runs. No appreciable isomerization of *cis*- to *trans*-stilbene was observed. All these results unambiguously showed that *cis*-stilbene was actually undergoing a Br_2-catalyzed isomerization to its trans isomer during bromination.

Table IV. Reagent and Product Distribution during the Reaction of 2.5×10^{-3} M Bromine and *cis*-Stilbene in 1,2-Dichloroethane at 25 °C

time, min	products, %[a] 3	4	5	6
0				100
16	30	23	4	43
28	34.5	27	5	33.5
53	40	31	5.5	23.5
101	45	34	6.5	14.5
249	47	39	5	9

[a] Average of three measurements. Errors are ±2% of the quoted values.

Scheme II



Discussion

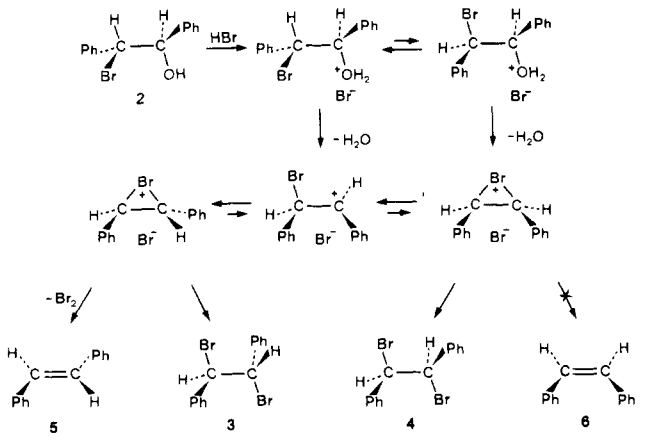
The results of the present investigation show that *trans*-stilbene, but not *cis*-stilbene, is produced in relevant amounts in the reactions of both *erythro*- and *threo*-2-bromo-1,2-diphenylethanol with hydrogen bromide in nonprotic low polarity solvents. The formation of the alkene at the expenses of the primary dibromide product having been excluded, the process can be rationalized as shown in Schemes II and III.

Under the employed conditions, C–O bond breaking in the oxonium species arising from protonation of bromohydrin **1** requires anchimeric assistance by the vicinal bromine,[29] as shown

(26) Price, C. C.; Berti, G. *J. Am. Chem. Soc.* **1954**, *76*, 1219–1221.
(27) Buckles, R. E.; Miller, J. L.; Thurmaier, R. J. *J. Org. Chem.* **1967**, *32*, 888–892.

(28) A slow isomerization of *d,l*- to *meso*-1,2-dibromo-1,2-diphenylethane has been reported to occur at room temperature when the solid *d,l* dibromide was left in contact with bromine vapors or when a carbon tetrachloride solution was treated with bromine or iodine (Buckles, R. E.; Steinmetz, W. E.; Wheeler, N. G. *J. Am. Chem. Soc.* **1950**, *72*, 2496–2499). Iodine-catalyzed isomerization in refluxing benzene has also been reported (Kwok, W. K.; Mathai, I. M.; Miller, S. I. *J. Org. Chem.* **1970**, *35*, 3420–3423).

Scheme III



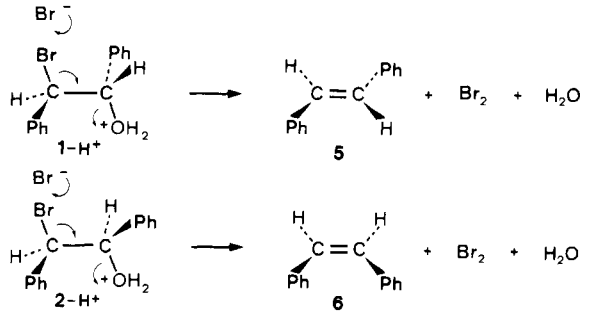
by the large reactivity difference exhibited by the two diastereomers **1** and **2** toward HBr, and leads to a bromonium ion intermediate. While the erythro compound **1** bears favorably arranged anti phenyl groups in the conformer having a bromine and oxonium group positioned in the necessary anti orientation, the threo isomer **2** has to adopt an unfavorable conformation with gauche phenyls in order to have bromine available for participation, and this difference is further increased on going to the transition states, which should be respectively similar to the trans and cis bromonium ions. For this reason and because of the benzylic nature of the involved incipient secondary bromocarbenium ion, assisted and unassisted processes are probably not very different in energy in the case of the threo bromohydrin (**2**). The solvent polarity may therefore be decisive in determining if anchimeric assistance is required or not for the C–O bond breaking in the latter compound.

The intermediate formed from the erythro bromohydrin (**1**) seems to have no tendency to rearrange to an open benzylic ion, as shown by the formation, as the only dibromide product, of the meso diastereomer **3** arising from anti nucleophilic attack by Br^- at either carbon of the trans bromonium ion. Some *d,l* dibromide would be expected from an open bromocarbenium ion intermediate, as found in the Br_2 addition to *trans*-stilbene (see below). Alternatively, Br^- can attack at the bromonium–bromine, thus removing Br^+ as molecular Br_2 and producing *trans*-stilbene. The ultimate fate of this released Br_2 would be to readd to the formed olefin and regenerate dibromide, so that the elimination reaction would escape detection, unless rebromination is slow enough to allow removal of Br_2 from the reaction mixture. This task is accomplished by the HBr stream.

In the case of threo bromohydrin (**2**), in the less polar chloroform solvent the loss of water from the oxonium intermediate may be anchimerically assisted by vicinal bromine, leading to the cis bromonium ion. The latter tends, however, to relieve its internal strain by rearranging to the trans ion through an open benzylic bromocarbenium ion (Scheme III). If the rate of the cis to trans bromonium ion rearrangement is comparable to that of collapse of the former intermediate to product, both the *d,l* and meso dibromides **4** and **3** are expected and are actually found (run 4 of Table I).

On the other hand, unassisted C–O bond breaking may occur in the reaction of **2** in the more polar, 1,2-dichloroethane solvent, giving the open benzylic bromocarbenium ion directly. The latter can undergo fast rotation and ring closure to the more stable trans bromonium species, which then collapses to give the meso product **3** as the only dibromide, as found in run 3 of Table I.

Scheme IV



Furthermore, also in the reactions of **2** the trans bromonium ion can undergo Br^+ abstraction by Br^- to give *trans*-stilbene and molecular Br_2, which is partially removed by the HBr stream. The very low amounts of *cis*-stilbene detected in these reactions indicate instead that either its possible precursor, the *cis* bromonium–bromide ion pair, is scarcely involved (reaction in 1,2-dichloroethane) or, if it is formed, its rate of rearrangement to the trans bromonium bromide species is higher than that of debromination to *cis*-stilbene (reaction in chloroform). The possibility that amounts of *cis*-stilbene much larger than the detected ones are actually formed but rapidly transformed under the reaction conditions can be safely excluded. In fact, its bromination in 1,2-dichloroethane would lead to a detectable amount of *d,l* dibromide **4** (see run 7 of Table III), which is instead absent in run 3 of Table I. In chloroform, on the other hand, *cis*-stilbene would add HBr to give a considerable amount of monobromo derivative (see run 8 of Table III), while only about 0.5% of 1-bromo-1,2-diphenylethane is found in run 4 of Table I.

We want to stress at this point that the lack of formation of relevant amounts of *cis*-stilbene allows us to exclude an E2-type bromide-promoted concerted elimination, similar to that often reported for the dehalogenations of vicinal dihalides,[30] from the oxonium–bromide intermediate arising from the threo bromohydrin (**2**) (Scheme IV). In fact, while such a process would lead to *trans*-stilbene from **1**, *cis*-stilbene would be obtained from **2**, in contrast with the observed formation of the trans olefin from both bromohydrins. The pathway sketched in Scheme III appears therefore to be the only reasonable mechanism for the conversion of **2** into olefin.[31] The E2-type process shown in Scheme IV would be consistent with the observed stereochemistry of olefin formation from the erythro bromohydrin (**1**). However, the bromonium ion mechanism of Scheme II seems to be much easier in the present case and offers the additional advantage that the reaction of both bromohydrins can be accommodated to the same reasonable mechanistic framework. A bromonium ion mechanism had also been favored on the basis of kinetic arguments over the E2-type elimination for the bromide-promoted formation of cycloalkenes in the solvolysis of *trans*-2-bromo-2-cycloalkyl brosylates.[4]

The steric course of the ionic bromination of stilbenes has been investigated by several workers.[22,23,32] However, the reported product distribution could admittedly be considered at best as semiquantitative estimates, and only the use of HPLC has now allowed us to obtain accurate values. Thus, the bromination of *trans*-stilbene has turned out to be not anti stereospecific as reported[22] but only moderately anti stereoselective. On the other hand, an increase in anti stereoselectivity of the bromine addition to *cis*-stilbene with decreasing solvent polarity had been reported[22,32] and is confirmed in the present work for both olefins.

The nature of the reaction intermediates has been suggested to change from an open benzylic ion, with free rotation about the

(29) (a) Winstein, S.; Lucas, H. J. *J. Am. Chem. Soc.* **1939**, *61*, 1576–1581. (b) Winstein, S.; Lucas, H. J. *J. Am. Chem. Soc.* **1939**, *61*, 2845–2848. (c) Winstein, S.; Buckles, R. E. *J. Am. Chem. Soc.* **1942**, *64*, 2787–2790. (d) Winstein, S. *J. Am. Chem. Soc.* **1942**, *64*, 2791–2792. (e) Winstein, S. *J. Am. Chem. Soc.* **1942**, *64*, 2792–2795. (f) Winstein, S.; Grunwald, E. *J. Am. Chem. Soc.* **1946**, *68*, 536–537. (g) Winstein, S.; Hanson, C.; Grunwald, E. *J. Am. Chem. Soc.* **1948**, *70*, 812–816. (h) Winstein, S.; Grunwald, E.; Buckles, R. E.; Hanson, C. *J. Am. Chem. Soc.* **1948**, *70*, 816–821. (i) Winstein, S.; Grunwald, E. *J. Am. Chem. Soc.* **1948**, *70*, 828–837.

(30) Baciocchi, E. *The Chemistry of Functional Groups*; Patai, S., Rappoport, Z., Ed.; Wiley: New York, 1983; Suppl. D, p 161.

(31) Alternative mechanisms, like concerted syn elimination or substitution–elimination, are considered less probable even for the bromide-promoted dehalogenations of *d,l*-1,2-dibromo-1,2-diphenylethane (see ref 30) and are even less likely under the conditions of the present reaction.

(32) Heublein, G. *J. Prakt. Chem.* **1966**, *31*, 84–91.

central C–C bond in more polar solvents,[33] to weakly bridged ions, with restricted rotation, or symmetrically bridged bromonium ions, with no rotation in less polar solvents.[22,23,32] An intermediate of the first type should undergo both anti and syn addition, while only anti addition is possible with an intermediate of the last type. This explains the slightly higher anti stereoselectivity observed in this work for the addition of Br_2 to *trans*-stilbene in the less polar solvent, where the bridged trans ion is expected to contribute more than the open ion. On the other hand, both an extensive cis to trans bromonium ion isomerization and a higher contribution of the open benzylic ion can account for the very low selectivity of *cis*-stilbene bromination in both solvents used in this work.

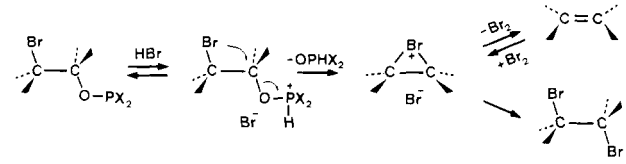
A stereospecific formation of anti adducts from stilbenes either when the bromination was carried out in the presence of bromide ions[22] or when a preformed tribromide salt was used as the reagent[34] had also been reported. The fact that a similar steric course is observed in this work also for the bromination of *trans*-stilbene performed in the presence of HBr suggests the intervention of a reactive tribromide species. An "HBr_3" reaction has been actually established kinetically[35] for brominations carried out in a nonpolar solvent, carbon tetrachloride, in the presence of excess HBr. If this reaction proceeds by a mechanism similar to that exhibited by the Br_3^- reagent, only the meso dibromide **3** should be formed from *trans*-stilbene. In fact, it has been shown[8,17] that in the Br_3^- reactions the rate- and product-determining step consists of a bromide attack on olefin·Br_2 CTCs, with little, if any, localization of positive charge at carbons in the transition state, and leads to exclusive anti addition.

In the case of the cis olefin, the situation is instead complicated by the fact that HBr addition or HBr-catalyzed isomerization to the trans isomer, depending on the solvent, is faster than bromination of *cis*-stilbene, so that the anti dibromo adduct **4** is always a minor product.

If we now look at the product distributions respectively reported in Table I for the reactions of bromohydrins **1** and **2** with HBr and in runs 1, 2, 5, and 6 of Table III for the addition of Br_2 to stilbenes, we always observe different dibromide ratios. This is at first sight surprising, since the same bridged cationic species are expected as the intermediates of both types of reactions. The discrepancy may be partially accounted for by recognizing that different counteranions are produced in the two reactions. While bromine addition to stilbenes leads to bromonium–tribromide ion pair intermediates, as shown by the second-order dependence of the rate on Br_2,[5,8] bromonium–bromide species are formed in the reactions of bromohydrins with HBr. Furthermore, in the later reactions the Br^- ion is likely to be hydrogen bonded to the released water molecule. This may well increase the lifetime of the ion couple, thus allowing a more extensive or even complete rearrangement of the cis bromonium ion or of the open ion, first formed from the threo bromohydrin **2**, to the more stable trans ion. This could explain the formation of the meso diastereomer **3** as the predominant or sole dibromide in this reaction, at variance with the very scarce stereoselectivity observed in the bromination of *cis*-stilbene.

This hypothesis, however, can hardly account for the complete suppression of formation of the *d,l* dibromide **4**, which is obtained in 20–32% yield by bromination of *trans*-stilbene, in the reactions of the erythro bromohydrin (**1**) with HBr. A more convincing rationalization consists in admitting that the reverse reaction of the trans bromonium–bromide ion pair to *trans*-stilbene shown in Schemes II and III proceeds to a much higher extent than that inferred on the basis of the recovered olefin. Since it has been shown that bromination of *trans*-stilbene in the presence of excess HBr leads to the meso diastereomer **3** as the only dibromide, an extensive formation of this olefin followed by its rebromination may rationalize the steric course of the reactions of both bromohydrins **1** and **2** with HBr. It must be stressed, in this respect,

Scheme V



that the amounts of olefin detected in these reaction mixtures depend critically on the efficiency with which the released Br_2 is prevented from readding by removal. Another factor tending to reduce the detected amount relative to the actually formed amount of olefin is the above-mentioned acid-catalyzed oligomerization of *trans*-stilbene. Thus, the ratios of *trans*-stilbene to meso dibromide obtainable from Table I give only lowest limiting evaluations for the occurrence of the reversion of the bromonium–bromide ion pair to olefin. It can also be observed that experiments of the present type would fail to allow the isolation of olefin intermediates when they add Br_2 and/or HBr at much higher rates than stilbenes, as most aliphatic olefins do, unless a sufficiently reactive scavenger is added.

The formation of substantial amounts of monobromides was observed a few years ago during the conversion of vicinal bromohydrins into dibromides by phosphorus tribromide.[36] It was shown that this side reaction involved readdition of HBr to olefins produced from the first formed phosphite ester intermediates. The elimination required anti-oriented vicinal groups and the intervention of HBr. Two possible alternative mechanisms were suggested, the one involving a tervalent phosphorus-promoted concerted anti elimination, the other an intramolecular displacement of bromine by phosphorus to give a four-membered cyclic intermediate, followed by collapse to olefin and a $POBrX_2$ species. In light of the results of the present investigation, the simpler mechanism shown in Scheme V seems more attractive. Thus, the conversion of bromonium–bromide ion pair intermediates formed from bromohydrins or their esters to the parent olefins would appear to be a quite general process.

The presence of *trans*-stilbene, besides the unreacted cis isomer observed in this work during the course of the bromination of the latter olefin, confirms the previously reported isomerization of starting material recovered from the bromination of *cis*-stilbene in 1,2-dichloroethane[22] and in acetic acid.[23] The occurrence of a free-radical-catalyzed rearrangement as well as of a HBr-catalyzed rearrangement of the olefin has been excluded by independent experiments. A Br_2-catalyzed debromination of the primarily formed dibromides can be rejected on the following grounds. No interconversion between the dibromides was observed when both pure **3** and **4** were left in the presence of Br_2 in 1,2-dichloroethane for times much longer than those of the bromination of *cis*-stilbene analyzed in Table IV. A debromination of either dibromide to *trans*-stilbene followed by rebromination would instead lead to mixtures of **3** and **4**, since this olefin has been shown to add Br_2 in a nonstereospecific way.

The observed rearrangement of *cis*- to *trans*-stilbene in the presence of Br_2 can therefore be rationalized only by the formation of a bromination intermediate which can equilibrate to its more stable form and release Br_2 to give the trans olefin. In other words, a process similar to that outlined in Scheme III for the intermediate ions generated from *threo*-2-bromo-1,2-diphenylethanol occurs also during the bromination of *cis*-stilbene in the same solvent, where the same cationic intermediate is coupled to a tribromide in place of a bromide ion.

It may seem surprising at first sight that a perfectly linear first-order plot (Figure 1) is obtained for the kinetics of the bromination of *cis*-stilbene carried out under the conditions of the run analyzed in Table IV, since two isomeric olefins are involved, which are brominated at rather different rates, and whose ratio increases during the course of the reaction. It can be easily calculated, however, from the data of Table IV that the rate of

(33) (a) Ruasse, M.-F.; Dubois, J.-E. *J. Org. Chem.* **1972**, *37*, 1770–1778. (b) Dubois, J.-E.; Ruasse, M.-F. *J. Org. Chem.* **1973**, *38*, 493–499.
(34) Fieser, L. F. *J. Chem. Educ.* **1954**, *31*, 291–297.
(35) Hart, L. S.; Whiting, M. C. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1087–1092.
(36) Bellucci, G.; Marioni, F.; Marsili, A.; Barili, P. L.; Berti, G. *Chem. Commun.* **1969**, 1017–1018.

consumption of Br_2 by *trans*-stilbene at half reaction is about 50 times lower than that by the cis isomer and must be also lower during the first half-life. Furthermore, the ratio of these rates remains <10 up to about 85% conversion. The measured reaction rate is therefore substantially that of *cis*-stilbene, with an insignificant contribution by that of the trans isomer produced during the course of the reaction, and only at very high conversion, when the Br_2 concentration is too low to be accurately measured, would the two rates be comparable and deviations from the linear third-order plot be observed.

The interpretation of structural effects on the rates of bromination of ring-substituted *trans*-stilbene in methanol[33] and in carbon tetrachloride[37] has been based on the assumption that the rate-determining step, considered to be the transformation of CTCs formed in the preequilibrium step into ionic intermediates, is not reversible. The irreversibility of this step in methanol was deduced[33a] from the linear dependence of the function $k_{obsd}(1 + K[Br^-])$, where k_{obsd} is the experimentally observed second-order rate constant and K is the formation constant of the Br_3^- ion, on the concentration of added bromide ion.[38] However, the reversal of intimate ion pair intermediates would not be kinetically monitorable.

The results of the present investigation show that, even in the most favorable case of *cis*-stilbene bromination, irreversibility cannot be revealed by simple kinetic measurements. As a consequence, no direct evidence could be gained for or against the reversible formation of a bromonium–tribromide ion pair in the bromination of *trans*-stilbene. However, we cannot see any reason why the trans bromonium–tribromide intermediate would release Br_2 to give *trans*-stilbene when it is formed by rearrangement of the ion pair intermediate arising from *cis*-stilbene but not when it is directly generated from *trans*-stilbene and Br_2. The formation of *trans*-stilbene and dibromide in comparable ratios observed both from *erythro*- and *threo*-2-bromo-1,2-diphenylethanol and HBr is in agreement with this assumption. In fact, these reactions have been shown to involve a trans bromonium–bromide ion pair, which is generated directly from the former and through a rearrangement of the first formed intermediate by the latter bromohydrin. It can therefore be safely concluded that under the conditions of the present investigation the bromination of both stilbenes involves a reversible electrophilic step.

We admit that stilbenes are particular olefins and that it would be hazardous to assume the reversibility of the electrophilic step as a general feature of olefin bromination on the sole basis of the present results. Yet, the results reported by Brown[4] and a reinterpretation of our earlier results[36] indicate that under appropriate conditions also bromonium ions of simple aliphatic structure can actually suffer reversion to the parent olefins. Clearly, further investigation in this direction is highly desirable since, as recently stressed by Brown,[4] "unless specifically accounted for, the presence of reversibility during the course of bromination introduces a rather severe complication into kinetic studies", the observed rates resulting lower than what they would be in the absence of such reversibility.

Indeed, the evidence that olefin·Br_2 CTCs formed in a preequilibrium step are involved as essential intermediates of olefin bromination[5] had already cast some doubt on the reliability of structure–reactivity correlations when structural effects on this preequilibrium are ignored.[8b] A conclusive demonstration of the general occurrence of reversibility of bromonium ion formation under the bromination conditions would involve the additional necessity of a detailed knowledge of structural effects also on the extent of reversibility in the formation of the ionic intermediates of these reactions, if a satisfactory rationalization of structure–reactivity correlations is to be obtained.

Experimental Section

Materials and Methods. Commercial *cis*-stilbene (Aldrich >97%) was fractionally distilled, and a fraction with bp 93 °C/5 mm was collected. *trans*-Stilbene (Schuchardt) was crystallized from ethanol, mp 124–125 °C.

erythro-2-Bromo-1,2-diphenylethanol (**1**) was prepared from *trans*-stilbene as reported by Dalton.[39] The crude product was purified by column chromatography (Kiesel-gel S, 150–230-mesh ASTM, Merck), using 9:1 hexane/ethyl acetate as the eluent, and crystallized from hexane: mp 83–84 °C [lit.[39] mp 84.5–85.5 °C].

threo-2-Bromo-1,2-diphenylethanol (**2**) was obtained from *cis*-stilbene with the same method[39] and purified by TLC (PSC Fertigplatten Kiesel-gel 60 F254, Merck, 9:1 hexane/ethyl acetate), followed by crystallization from hexane: mp 50–51 °C [lit.[39] mp 51–52 °C].

meso-**3** and *d,l*-1,2-dibromo-1,2-diphenylethane (**4**) were respectively prepared from *trans*- and *cis*-stilbene with tetrabutylammonium tribromide as reported by Buckles:[22] meso isomer **3**, mp 237 °C [lit.[22] mp 237–239 °C dec]; *d,l* isomer **4**, mp 110 °C [lit.[22] mp 110–111 °C].

All products were >99.5% pure by HPLC.

1,2-Dichloroethane and bromine (both C.Erba RPE >99.5%) were treated as previously reported.[16] Chloroform (C.Erba RPE >99.5%) was distilled immediately before use. Gaseous HBr (Matheson) was 99.8% pure.

Evaporation of the reaction mixtures was carried out in vacuo (rotatory evaporator).

Reagent purity and product distributions were determined by HPLC using a Waters 6000A apparatus equipped with a 25-cm Hypersil 10 ODR column (HPLC technology) and UV detector (λ 240, 280 nm) with 70:30 methanol/water as the eluent at a flow rate of 1 mL/min. The crude reaction mixtures were dissolved in the same solvent mixture employed as the eluent for the HPLC analysis (70:30 methanol/water), and the appropriate amounts of a methanol stock solution of 5*H*-dibenzo-[*b,f*]azepine-5-carboxyamide were added as an internal standard. The product yields were evaluated by using calibration curves obtained for each product and the standard. The analysis of the solid mixtures of dibromides **3** and **4** turned out to be particularly critical, owing to the very low solubility of the meso diastereomer. Reproducible results were obtained only when the crude products were dissolved in large amounts of the 70:30 methanol/water mixture (ca. 500 mL for 10 mg of product). Attempts at using more concentrated solutions in methanol or acetonitrile led to undervaluation of **3** due to its precipitation when the solutions came into contact with the aqueous methanol in the instrument.

NMR, IR, and UV spectra were respectively obtained on an EM 360A Varian spectrometer and on Pye-Unicam SP3-300 and Pye-Unicam SP8-400 spectrophotometers. Melting points were obtained by using a Kofler apparatus and were uncorrected.

Reactions of Bromohydrins with HBr. Gaseous HBr was bubbled into ca. 10^{-2} M solutions of *erythro*-**1** or *threo*-2-bromo-1,2-diphenylethanol (**2**) in 1,2-dichloroethane or chloroform (10 mL) at 10 °C during the times reported in Table I. The reaction mixtures, which were about 0.5 M in HBr, were then washed with water, dried ($MgSO_4$), and evaporated. The residues were subjected to HPLC analysis. The product yields are reported in Table I.

Treatment of Dibromides with HBr. Gaseous HBr was bubbled for 1 h into 10 mL of ca. 5×10^{-3} M solutions of *meso*-**3** or *d,l*-1,2-dibromo-1,2-diphenylethane (**4**) in 1,2-dichloroethane or chloroform. After the usual workup, HPLC analysis showed that both dibromides were recovered unchanged in >95% yield.

Reactions of Olefins with HBr. A. Solutions of ca. 5×10^{-3} M *cis*-stilbene (**6**) or *trans*-stilbene (**5**) in 1,2-dichloroethane or chloroform were saturated with gaseous HBr at room temperature. The final concentrations of HBr were around 0.5 M. Samples were withdrawn at intervals, washed with water, dried ($MgSO_4$), and evaporated, and the residues were analyzed by HPLC. The product yields are reported in Table II.

B. 1-Bromo-1,2-diphenylethane (oil) was isolated in 50% yield by preparative TLC (PSC Fertigplatten Kiesel-gel 60 F254, Merck, 95:5 hexane/ethyl acetate) after 18-h reaction of *cis*-stilbene (0.1 g) with saturated gaseous HBr solution in chloroform (80 mL): ^1H NMR ($CDCl_3$) δ 3.6 (d, 2 H, CH_2, J = 8 Hz), 5.2 (t, 1 H, CHBr, J = 8 Hz), 7.3 (m, 10 H, aromatics).

C. A solution containing *cis*-stilbene (3×10^{-3} M) and HBr (1.5×10^{-4} M) in 1,2-dichloroethane was thermostated at 25 °C for 3 h. After the usual workup, the residue was analyzed by HPLC. No isomerization to *trans*-stilbene was observed.

Reactions of Olefins with Br_2. A. In the Absence of HBr. Solutions of *cis*- or *trans*-stilbene (6×10^{-3} M, 1.5 mL) in 1,2-dichloroethane or chloroform were mixed with equal volumes of 6×10^{-3} M Br_2 solutions in the same solvent at room temperature. After the reactions were complete, the solvent was evaporated, and the crude residues were ana-

(37) Heublein, G.; Schultz, E. *Z. Chem.* **1969**, *9*, 147–148.
(38) (a) Bartlett, P. D.; Tarbell, D. S. *J. Am. Chem. Soc.* **1936**, *58*, 466–474. (b) Dubois, J.-E.; Garnier, F. *Bull. Soc. Chim.* **1967**, 4512–4514.
(39) Dalton, D. R.; Dutta, V. P.; Jones, D. C. *J. Am. Chem. Soc.* **1968**, *90*, 5498–5501.

lyzed by HPLC. The product yields are reported in Table III.

B. In the Presence of HBr. Equimolar amounts of a ca. 1.5×10^{-2} M solutions of Br_2 in 1,2-dichloroethane or chloroform were added dropwise to 20 mL of 3.5×10^{-2} M solutions of *cis*- and *trans*-stilbene in the same solvents, whereas HBr was bubbled through these solutions. After the addition was complete, the reaction mixtures were washed with water, dried ($MgSO_4$), and evaporated, and the crude residues were analyzed by HPLC. The results are reported in Table III.

Treatment of Dibromides with Br_2. Equimolar amounts of *meso*-**3** or *d,l* dibromide **4** and of Br_2 were mixed in 1,2-dichloroethane (ca. 3×10^{-3} M) and left at room temperature for 3 days. The solutions were then washed with saturated aqueous $NaHSO_3$ and water, dried ($MgSO_4$), and evaporated. The HPLC analysis showed that both dibromides were quantitatively recovered.

Kinetic Measurements. Bromine solutions in 1,2-dichloroethane were prepared shortly before use and the concentrations were determined from the UV-vis spectra (ϵ_{max} 211 M^{-1} cm^{-1} at λ_{max} 409 nm) and adjusted to twice the desired initial concentrations (ca. 3×10^{-3} M) in the kinetic runs. In a few runs the solvent was preventively saturated with oxygen. These solutions were prethermostated at 25 °C and mixed with equal volumes of prethermostated olefin solutions of identical concentrations in the same solvent. The reactions were followed at 25 ± 0.05 °C (Lauda MK 70 constant-temperature circulating bath) by monitoring the decrease in absorbance of Br_2 at 409 nm and recorded for more than three half-lives. The absorbance/time data were fitted to eq 3 and the third-order rate constants obtained with the usual linear least-squares procedure. The reported values are the average of four independent measurements. Errors are given as standard deviations obtained from the deviations of individual measurements from the average values.

$$1/A^2 = (2k_3/\epsilon_{Br_2}^2)t + 1/A_0^2 \quad (3)$$

Product Distribution during Bromination. A 2.5×10^{-3} M solution of *cis*-stilbene and Br_2 in 1,2-dichloroethane thermostated at 25 ± 0.05 °C was divided into two parts. One part was used to follow the reaction kinetics monitoring the absorbance of Br_2. Samples were simultaneously withdrawn at intervals from the second part, and the unreacted Br_2 was immediately reduced by adding solid $Na_2SO_3 \cdot 7H_2O$. After filtration, these samples were directly analyzed by HPLC. The amounts of unreacted olefin and of dibromide products were deduced from the absorbance measurements, while the distribution of the total olefin between *cis*- and *trans*-stilbene as well as that of the total dibromides between the meso and *d,l* isomers were calculated from the chromatograms using appropriate calibration curves. The results are reported in Table IV. Experiments carried out under identical conditions but with oxygen-saturated 1,2-dichloroethane gave the same results.

Acknowledgment. This work was supported by a grant from the Consiglio Nazionale delle Ricerche and from the Ministero della Pubblica Istruzione. We acknowledge Prof. R. S. Brown for his comments about the manuscript.

Registry No. 1, 10368-43-1; **2**, 74892-78-7; *meso*-**3**, 13440-24-9; (*dl*)-**4**, 13027-48-0; **5**, 103-30-0; **6**, 645-49-8; HBr, 10035-10-6; Br_2, 7726-95-6.

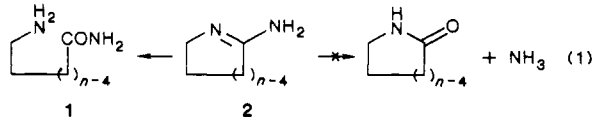
Hydrolysis of Unsymmetrical Acetamidines: Leaving Abilities and Stereoelectronic Effects

Charles L. Perrin* and Oswaldo Nuñez

Contribution from the Department of Chemistry, D-006, University of California, San Diego, La Jolla, California 92093. *Received July 11, 1986*

Abstract: Unsymmetrical acetamidines hydrolyze in alkaline D_2O to a mixture of two acetamides and two amines. Product ratios from three N-methylated acetamidines and five *N*-alkyl-*N'*-methylacetamidines were determined by NMR. The direction of cleavage is determined largely by the relative basicities of the two amines, rather than by the relative basicities of the two nitrogens in the tetrahedral intermediate. Steric repulsion in the product amides can also affect the product ratio, but only slightly. There is also a novel configurational effect, which favors cleavage of the nitrogen whose alkyl group is (*Z*) in the amidinium ion. This arises from a stereoelectronic preference for cleavage of a leaving group that is antiperiplanar to two lone pairs in the tetrahedral intermediate. However, it is concluded that this preference is weak. These results have guided the design of a test of this stereoelectronic preference in the hydrolysis of a set of cyclic amidinium ions where product stabilities and leaving abilities can be closely matched.

Recently the formation of aminoamide (**1**), rather than lactam + NH_3, from the hydrolysis (eq 1) of cyclic amidines (**2**, n = 5, 6), has been presented[1] as the first unambiguous evidence for



1 **2**

Deslongchamps' theory of stereoelectronic control.[2] In this reaction the products are of nearly equal stability (except for entropy, which probably does not affect the kinetics[3]), in contrast to the corresponding ortho ester hydrolysis,[4] where a lactone is appreciably less stable[5] than is an ordinary ester. Yet it is still not clear that eq 1 can be an unambiguous test of the theory. Even though product stabilities are matched, leaving abilities may not be.

Hydrolysis of an unsymmetrical amidine, via the hemiortho amide and its conjugate base (**3**), cleaves preferentially the more basic amine,[6] although there may be exceptions.[7] Basicity governs

(1) Perrin, C. L.; Arrhenius, G. M. L. *J. Am. Chem. Soc.* **1982**, *104*, 2839.
(2) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon: Oxford, 1983.
(3) Kirby, A. J. *The Anomeric Effect and Related Stereoelectronic Effects at Oxygen*; Springer: Berlin, 1983; pp 103-104.
(4) Deslongchamps, P.; Atlani, P.; Frêhel, D.; Malaval, A.; Moreau, C. *Can. J. Chem.* **1974**, *52*, 3651. Deslongchamps, P.; Chênevert, R.; Taillefer, R. J.; Moreau, C.; Saunders, J. K. *Ibid.* **1975**, *53*, 1601. Deslongchamps, P.; Lessard, J.; Nadeau, Y. *Ibid.* **1985**, *63*, 2485.
(5) Huisgen, R.; Ott, H. *Tetrahedron* **1959**, *6*, 253. Jones, G. I. L.; Owen, N. L. *J. Mol. Struct.* **1973**, *18*, 1. Peterson, M. R.; Csizmadia, I. G. *J. Am. Chem. Soc.* **1979**, *101*, 1076 and references cited. Grindley, T. B. *Tetrahedron Lett.* **1982**, *23*, 1757.
(6) Weiner, M. L. *J. Org. Chem.* **1960**, *25*, 2245. Burdick, B. A.; Benkovic, P. A.; Benkovic, S. J. *J. Am. Chem. Soc.* **1977**, *99*, 5716. Benkovic, S. J.; Barrows, T. H.; Farina, P. R. *Ibid.* **1973**, *95*, 8414. Benkovic, S. J.; Bullard, W. P.; Benkovic, P. A. *Ibid.* **1972**, *94*, 7542. Čegan, A.; Šlosar, J.; Večerá, M. *Collect. Czech. Chem. Commun.* **1978**, *43*, 134. Meyers, A. I.; Ten Hoeve, W. *J. Am. Chem. Soc.* **1980**, *102*, 7125.

0002-7863/87/1509-0522$01.50/0