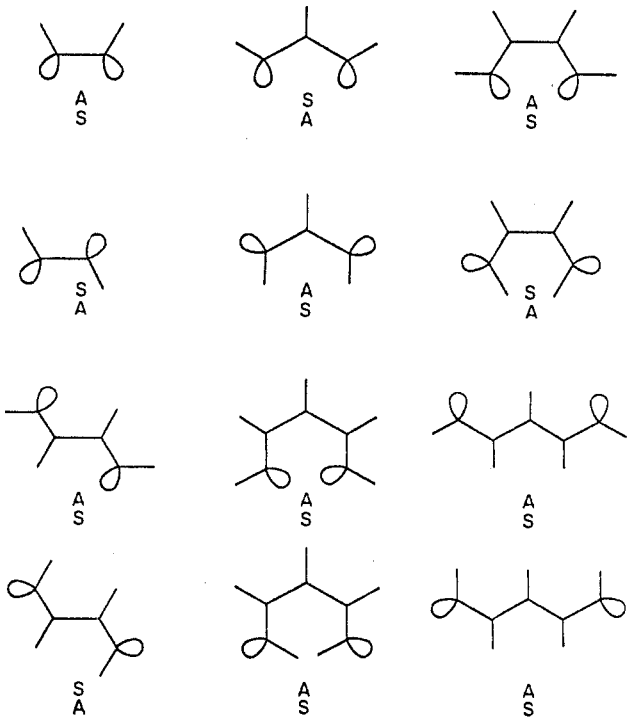
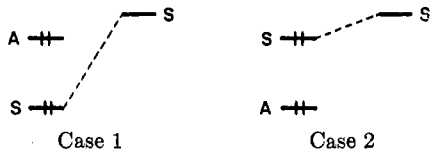


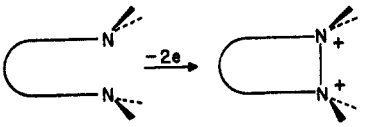
Figure 9. Some model arrangements of orbital lobes and intervening σ bonds. The symbols below each figure give the level ordering obtained for model compounds.

two nitrogen lone pairs. Clearly the symmetric position is more stabilized in case 2, the result of through-bond



coupling.

Consider also the likelihood of carrying out an oxidative cyclization of the type shown below. If one wants to form a bond between the two nitrogens one



clearly should seek out a situation with strong direct interaction. In that case the two electrons will be removed from an A orbital, decreasing N–N antibonding and correspondingly increasing bonding.

Summary

This paper has been concerned with a necessary addendum to the chemist's view of a molecule. Localized orbitals or groups of orbitals may interact with each other directly, through space, or indirectly, through other bonds in the molecule. The latter interaction may operate over surprisingly long distances. The primary effects of such interaction and their most direct measure are through ionization potentials and electronic spectra. Stability and reactivity are affected as well. The analysis of these interactions is most conveniently made through the language of perturbation theory; here, as everywhere, the role of symmetry is paramount.[20]

It is a pleasure to acknowledge the aid of able coworkers, prime among them Akira Imamura and Rolf Gleiter, the congenial interaction with Edgar Heilbronner, the inspiration of the chemical literature, the pleasant environment of Cornell, and the generous sponsorship of the National Science Foundation, the National Institutes of Health, the Chevron Research Corporation, and the Sloan Foundation.

(20) *Editor's note:* Readers may be interested in the comments of a congenial reviewer of Hoffmann's manuscript: "Somehow the problems facing an author writing for *Accounts of Chemical Research* are similar to those we meet in the sexual education of our children. To begin with you have to give them the basic facts of life in a grossly simplified way, skipping the finer technical details and the complications that usually contribute to the interaction ⟨♀|H|♂⟩. After this, there are two possibilities: (a) let the little dears find out by themselves, or (b) tell them a bit more about these problems. From the "Statement of Policies and Procedures" I see that the editors would prefer course b. However your contribution falls clearly into category a . . . ."

Regiospecific and Stereospecific Introduction of Azide Functions into Organic Molecules

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The synthetic chemist has at his disposal a variety of methods for the stereospecific introduction of oxygen functions into the carbon skeleton, *e.g.*, *via* opening of epoxides, hydroboration of olefins, or reduction of ketones. Until recently the same has not been true for functional groups containing nitrogen.

Since halogens, X–X, usually add stereoselectively to multiple bonds, we envisaged a route in which X–N moieties would add across the carbon–carbon double bond. Indeed, when we explored iodine isocyanate (INCO) additions to alkenes, we found a useful route for the stereospecific synthesis of carbamates, aziridines, and oxazolidones, as well as cis or trans 2-amino alcohols.[1]

(1) (a) A. Hassner and C. H. Heathcock, *Tetrahedron Lett.*, 393 (1963); (b) C. H. Heathcock and A. Hassner, *Angew. Chem.*, **75**, 344 1963); (c) A. Hassner and C. H. Heathcock, *Tetrahedron*, **20**, 1037 (1964); (d) A. Hassner, M. E. Lorber, and C. H. Heathcock, *J. Org. Chem.*, **32**, 540 (1967).

Organic azides have been of recent interest in photochemistry,[2] in cycloadditions,[3] and as precursors to amine functions. Furthermore the ambident and amphoteric character of the azide function is indicated by its participation in electrophilic as well as in nucleophilic reactions. Since stereospecific methods for the introduction of an azide function were not well known, we decided to determine the feasibility of X–N_3 additions to olefins.

In studying the addition of an unsymmetrical reagent X–Y to an unsymmetrical olefin RCH=CHR′, we were soon faced with the problem of establishing orientation as well as stereochemistry in the adduct. The Markovnikov rule is often inapplicable, and consequently we adopted the general term *regioselectivity* (latin, regio = direction) to describe directional selectivity in bond breaking or making, regardless of the mechanism involved.[4] Thus, the exclusive formation of **2** in the IN_3 addition to *tert*-butylethylene (**1**) is described as I-*tert*-butyl regiospecific.

$$\underset{\mathbf{1}}{(CH_3)_3CCH{=}CH_2} + IN_3 \longrightarrow \underset{\mathbf{2}}{(CH_3)_3CCHCH_2N_3}\ (I)$$

Pure iodine azide (IN_3) is explosive, and its reported[5] synthesis from the highly explosive AgN_3 and I_2 was not only undesirable but led to a mixture of products on reaction with olefins. This problem was solved by devising special methods for the preparation of IN_3, BrN_3, and ClN_3. We succeeded in preparing iodine azide in solution in up to 0.25 *M* quantities by the reaction

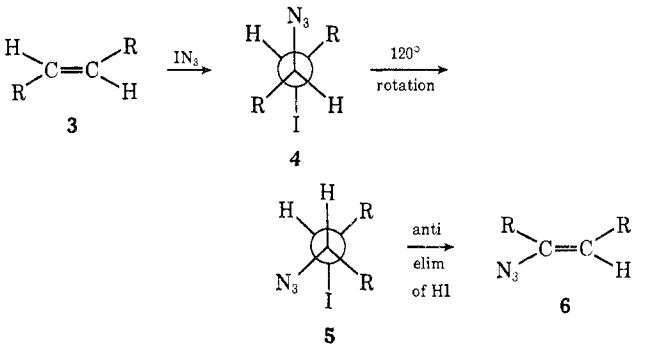
$$ICl + NaN_3 \longrightarrow IN_3 + NaCl$$

in polar organic solvents.[6] The other halogen azides were formed in a two-phase system (water–pentane) by the interaction of Br_2 or Cl_2 with NaN_3 in the presence of acid.[7]

Iodine Azide Additions

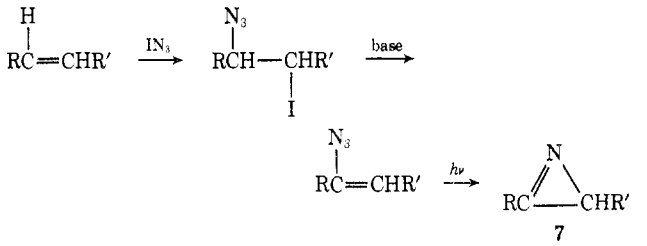
Stereochemical Aspects. When olefins were added at −10 to 25° to a solution of 1 equiv of IN_3 in acetonitrile, 1:1 adducts were formed in excellent yield. The addition appeared to be stereospecific, with cyclohexene (**8**) furnishing exclusively *trans*-2-azidocyclohexyl iodide (**9**), while *cis*- and *trans*-2-butene yielded the threo and erythro adducts, respectively.[6] This stereospecificity is noteworthy in view of Minisci's findings that the elements of ClN_3 add nonstereospecifically to cyclohexene.[8]

Although isomeric cis and trans olefins gave different adducts, it was necessary to show whether syn or anti addition had taken place. To this end, and with the expectation of finding a route to vinyl azides which we hoped to use for photolytic studies, we attempted to eliminate HI from the β-iodoalkyl azides. Potassium *tert*-butoxide and 1,4-diazabicyclo[2.2.2]octane (DABCO) proved to be the reagents of choice, and as anticipated the elimination proceeded in an anti fashion. In open-chain systems the propensity for anti coplanar elimination of HI overcomes any unfavorable conformational effects; therefore elimination occurs from conformation **5** rather than from **4**, giving rise to cis vinyl azides **6** from trans alkenes **3** and to trans vinyl azides starting with cis olefins.[9a]



3 **4** **5** **6**

In most open-chain systems the HI elimination is regiospecific, leading to vinyl azides rather than to allyl azides. This reflects a lower energy transition state, leading to the more substituted olefin. We took advantage of this fact to develop, by photolysis of these vinyl azides, a general synthesis of the 1-azirine ring system **7**.[9b]



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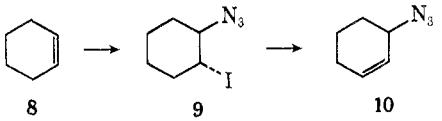
Consistent with the requirements for anti-coplanar HI elimination is the fact that trans iodo azide **9** leads to allyl azide **10** rather than to a vinyl azide, the formation of which would require a syn elimination of HI.



8 **9** **10**

In eight-membered rings both syn and anti elimination becomes possible, leading to a trans or a cis olefin, respectively. When we treated the IN_3 adduct **12** from *cis*-cyclooctene (**11**) with base we obtained vinyl azide **13** which was stable at room temperature but converted to azirine **14** on photolysis. The thermal stability of **13** and its nmr spectrum (vinyl H at τ 4.7) render a *trans*-azidocyclooctene structure unlikely. In

(2) See, for instance, D. H. R. Barton and A. N. Starratt, *J. Amer. Chem. Soc.*, **87**, 2444 (1965); G. T. Tisue, S. Linke, and W. Lwowski, *ibid.*, **89**, 6303 (1967); F. D. Lewis and W. H. Saunders, Jr., *ibid.*, **90**, 7033 (1968).

(3) See, for instance, R. Huisgen, *Angew. Chem.*, **75**, 741 (1963); G. L'abbé, *Chem. Rev.*, **69**, 345 (1969).

(4) A. Hassner, *J. Org. Chem.*, **33**, 2684 (1968).

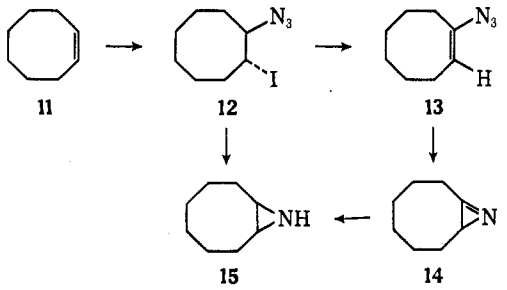
(5) A. Hantzsch, *Ber.*, **33**, 524 (1900).

(6) (a) A. Hassner and L. A. Levy, *J. Amer. Chem. Soc.*, **87**, 4203 (1965); (b) F. W. Fowler, A. Hassner, and L. A. Levy, *ibid.*, **89**, 2077 (1967).

(7) (a) A. Hassner and F. Boerwinkle, *ibid.*, **90**, 216 (1968). (b) A. Hassner and F. Boerwinkle, *Tetrahedron Lett.*, 3309 (1969).

(8) F. Minisci, *Chim. Ind. (Milan)*, **49**, 705 (1967).

(9) (a) A. Hassner and F. W. Fowler, *J. Org. Chem.*, **33**, 2686 (1968); (b) A. Hassner and F. W. Fowler, *J. Amer. Chem. Soc.*, **90**, 2869 (1968).

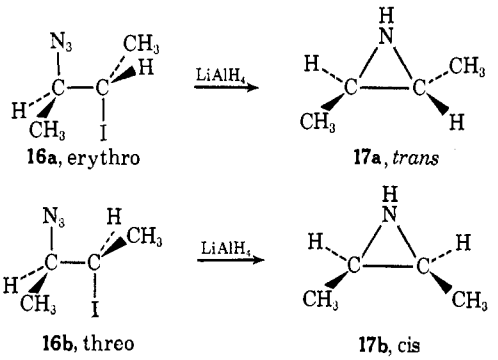


all vinyl azides, the proton trans to the azido group is significantly shielded in the nmr relative to the cis isomer (see Chart I).[9a] This is also true when the *cis*-R substituent is phenyl. The nmr spectrum of **13** fits a *cis*-dialkylvinyl azide structure; hence syn elimination of HI had taken place in the cyclooctane system.[10]

Chart I
Olefinic Proton Absorption in Vinyl Azides

R = alkyl: τ 4.7–4.9 τ 5.3–5.45
R = phenyl: τ 3.74 τ 4.09

Proof for anti addition of IN_3 is also provided by the $LiAlH_4$ reduction of the adducts. This reaction was studied in detail and found to be a highly stereospecific and useful method of aziridine synthesis.[11a] Thus, *erythro*-2-azido-3-iodobutane (**16a**), the product of IN_3 addition to *trans*-2-butene, gives only *trans*-2,3-dimethylaziridine (**17a**), whereas the threo isomer **16b** (from *cis*-2-butene) furnished *cis*-dimethylaziridine (**17b**).

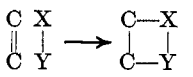


16a, erythro **17a**, *trans*

16b, threo **17b**, cis

The reductive ring closure of **9** or **12** to fused aziridines (*e.g.*, **15**) in essentially quantitative yield is a further indication of the trans stereochemistry in these IN_3 adducts.

Based on these facts, we suggested that the IN_3 addition involved electrophilic attack on the olefin with formation of a three-membered-ring iodonium ion, *e.g.*, **19**. It may be of interest to comment here on the reason for the common preponderance of anti addition over syn addition of halogens or halogenoids to olefins, especially since a concerted collapse of type



appears most reasonable. However, orbital symmetry considerations[11b] suggest that concerted nonphotochemical syn addition ($2_s + 2_s$) of X–Y to olefins is forbidden, whereas anti addition ($2_s + 2_a$) is allowed. From a simpler point of view it becomes clear that concerted syn addition of X–Y to a double bond should be most favorable when X–Y is not easily polarized and its bond length approximates the C=C bond length. For instance, syn hydroboration of olefins can be explained by approach of the empty p orbital of boron to the π electrons of the double bond (probably complex formation), necessitating a parallel alignment of H in a manner similar to that indicated below. Since the B–H bond length corresponds within 0.2 Å to the C=C bond length, syn collapse can occur. This is not

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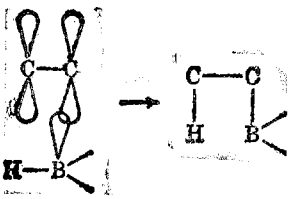
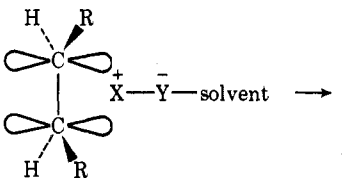


possible for IN_3 additions due to the large radius of iodine. If polarization of X–Y is facile, an ionic addition will be initiated by the approach of the electrophilic terminus of the reagent to the π cloud of the olefin. The most effective solvation of the transition state takes place when the positive end of the X–Y dipole approaches the π-electron cloud at right angles to the plane of the olefin, so that the negative portion of the X–Y dipole can be stabilized by solvation (see **18**).



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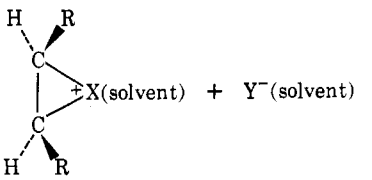

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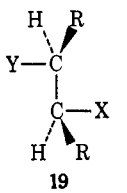


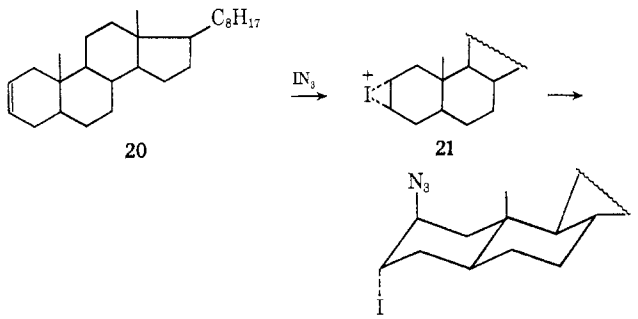
19

Once a three-membered-ring intermediate (**19**) is formed it follows that, unless equilibration to a free carbonium ion takes place, opening will preferentially

(10) This is consistent with recent findings by J. Sicher, *Collect. Czech. Chem. Commun.*, **32**, 2104, 2122 (1967).
(11) (a) A. Hassner, G. J. Matthews, and F. W. Fowler, *J. Amer. Chem. Soc.*, **91**, 5046 (1969); (b) R. B. Woodward and R. Hoffmann, *Angew. Chem., Intern. Ed. Engl.*, **8**, 781 (1969).

occur from the back side resulting in anti addition of X–Y. It is possible that, unlike in bromination of olefins, the rate-determining step in IN_3 additions involves opening of the cyclic ion **19** which is formed in a fast equilibrium step.

In conformity with the intermediacy of **21** is the IN_3 addition to 2-cholestene (**20**) which afforded the trans-diaxial adduct **22**.[6] This can be explained by ionic IN_3 attack on the π cloud of the olefin from the less hindered α side of the steroid. Stereoelectronic control favors diazial opening of the iodonium ion in a chair conformation.[12] Prior to these studies the major evidence for three-membered-ring iodonium ions had come from solvolysis reactions.[13] Recently Olah and coworkers[14] also provided spectral evidence for the presence of halonium ions in solution.

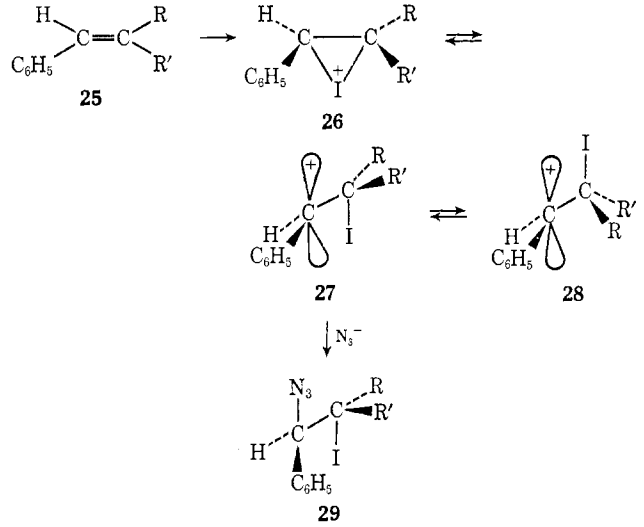


With 1-hexene (**23a**) or styrene (**23b**) the addition proceeded regiospecifically to yield the secondary azide **24a** or **24b**, respectively. This indicated to us that the reaction path involved either the free carbonium

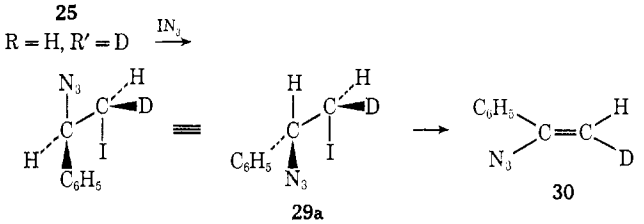
$$\underset{\mathbf{23}}{RCH{=}CH_2} + IN_3 \longrightarrow \underset{\mathbf{24}}{\underset{N_3}{\overset{|}{RCH}}{-}CH_2I}$$

a, R = *n*-butyl; **b**, R = C_6H_5

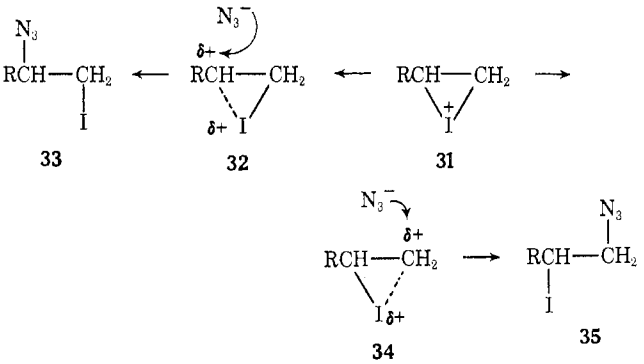
ion **27** or a three-membered-ring iodonium ion that is opened regiospecifically. A choice between these two intermediates might be possible on the basis of stereochemical observations in the IN_3 addition to β-substituted styrenes. These additions proceed stereospecifically anti, suggesting the involvement of **26**. However, these findings do not exclude the intermediacy of a benzylic cation in which there was a barrier to rotation (*i.e.*, from **27** to **28** or corresponding trigonal ions). To minimize nonbonded interactions during the rotation of **27** to **28** and to test whether conversion of **26** to a benzylic cation occurs before opening of the three-membered ring by N_3^-, we chose as a stereochemical substrate an olefin with the smallest β substituent, *e.g.*, *cis*-β-deuteriostyrene (**25**, R = H, R′ = D). When IN_3 was added to this olefin, **29a** was obtained which, on anti elimination of HI, gave exclusively α-azido-*trans*-β-



deuteriostyrene (**30**).[15] These results mitigate against equilibration of **26** with a benzylic cation.



Regiochemical Aspects. A good probe for the mechanism is often the regiochemistry of a reaction. The data discussed so far for the IN_3 addition to terminal olefins are consistent with the intermediacy of a three-membered ring ion, **31**, opening of which proceeds *via* the lower energy transition state (**32** rather than **34** when R can stabilize an incipient positive charge).



If the above considerations are valid, then an electron-withdrawing R group in **31** should destabilize transition state **32** relative to **34**. Indeed, we were able to show that ester **36a** leads to a 20:80 mixture of **35**:**33** (R = $CO_2C_2H_5$) and **36b** gave exclusively the I-carbonyl regiospecific IN_3 adduct **35**.[6] In the case of unsaturated ketones, a mixture of regioisomers was formed when R = CH_3 (**37a**) but only one isomer resulted from chalcone (**37b**).[16] These results indicate that there is a delicate balance involved in opening of iodonium ion intermediates adjacent to a carbonyl

(12) A. Hassner and C. H. Heathcock, *J. Org. Chem.*, **30**, 1748 (1965).

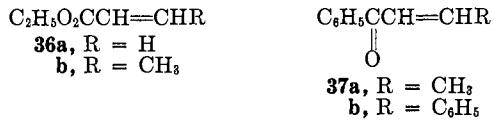
(13) (a) S. Winstein, E. Grunwald, and L. L. Ingraham, *J. Amer. Chem. Soc.*, **70**, 821 (1948); (b) H. J. Lucas and H. K. Garner, *ibid.*, **72**, 2145 (1950).

(14) G. A. Olah, J. M. Bollinger, and J. Brinich, *ibid.*, **90**, 2587 (1968).

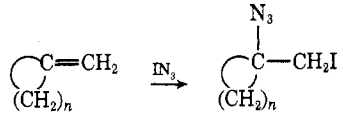
(15) A. Hassner, F. Boerwinkle, and A. B. Levy, *J. Amer. Chem. Soc.*, **92**, 4879 (1970).

(16) G. L'abbé and A. Hassner, *J. Org. Chem.*, in press.

group (**31**, R = R′C=O). In addition to the electronic factors mentioned above, one must consider the high propensity for nucleophilic displacements at the α carbon (more so for ketones than for esters).

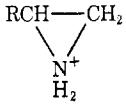


A further test is provided by the behavior of methylenecycloalkanes. In both **38** and **39**, electronic control (stabilization of a transition state of type **32** by the electron-donating ring residues) prevails with exclusive formation of **40** and **41**, respectively.[6] At this point, attension is called to the remarkable regioselectivity of the IN_3 reagent. By contrast, INCO addition to



38, $n = 3$ **40**, $n = 3$
39, $n = 5$ **41**, $n = 4$

methylenecyclohexane (**39**) or to 1-hexene (**23a**) gives a mixture of regioisomers,[17] and opening of the aziridium ion **42** also leads to regioisomeric halo amines depending on the nature of R.[18]



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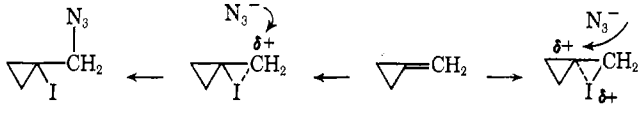
We predicted one exception among the methylenecycloalkanes with respect to the regiochemistry of IN_3 addition, namely, **43**, because transition state **44** (cyclopropylcarbinyl cation) is expected to be stabilized with respect to **46** (cyclopropyl cation). Indeed, we found that methylenecyclopropane (**43**) gave the IN_3 adduct **45** characterized by its mass spectrum ($C_3H_4I^+$ at m/e 167) and by HI elimination to a vinyl azide.[19] No elimination occurred on base treatment of **40** or **41**.

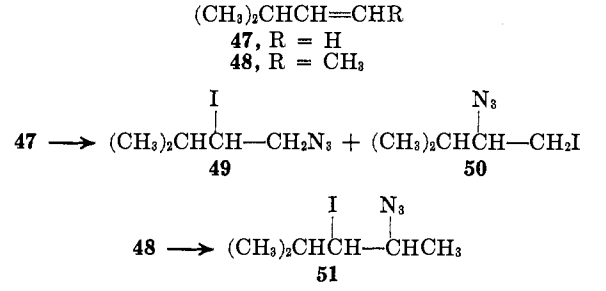


45 **44** **43** **46**

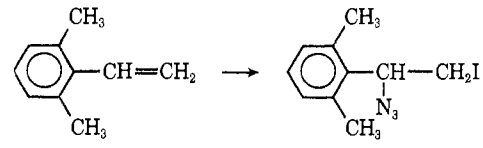
Next we tested neopentyl system **1** to determine whether the iodonium ion **31** (R = *tert*-C_4H_9) is opened with methyl rearrangement. We found that no methyl migration had occurred and that the IN_3 addition product **2** was of opposite regiochemistry from **33** (derived of 1-hexene).[9] It is obvious that the large *tert*-butyl group exerts a strong steric effect in the opening of the three-membered-ring iodonium ion **31**. Similar effects have been observed in the opening of three-membered-ring episulfonium ions.[20]

(17) A. Hassner, R. P. Hoblitt, C. Heathcock, J. E. Kropp, and M. Lorber, *J. Amer. Chem. Soc.*, **92**, 1362 (1970).
(18) J. S. Fruton in "Heterocyclic Compounds," Vol. I, R. C Elderfield, Ed., Wiley, New York, N. Y., 1950, p 69.
(19) A. Hassner, G. J. Matthews, and A. B. Levy, University of Colorado, unpublished results.

Even an isopropyl group can cause considerable hindrance in the opening of iodonium ions, and a particularly high degree of regioselectivity is noticed when the electronic effects of the substituents are balanced, *i.e.*, **47** gave a mixture of IN_3 adducts **49** and **50** whereas **48** gave solely the I-isopropyl regiospecific adduct (**51**).[9a]

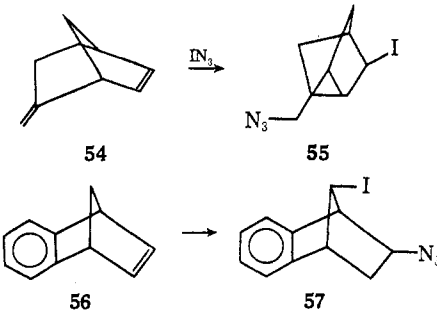


On the other hand, any steric effects appear compensated by electronic factors in the formation of **53** from 2,6-dimethylstyrene (**52**).[19]



52 **53**

Rearrangements. The data presented so far do not necessarily imply that a three-membered iodonium ion intermediate persists until attacked by a nucleophile and is never opened by neighboring group participation. In some systems the propensity for rearrangement is so large (lower transition state energies) that these processes do indeed take place. Examples are provided by methylenenorbornene (**54**) and benzonorbornadiene (**56**) which lead to rearranged products **55** and **57**, respectively, in almost quantitative yield.[21]

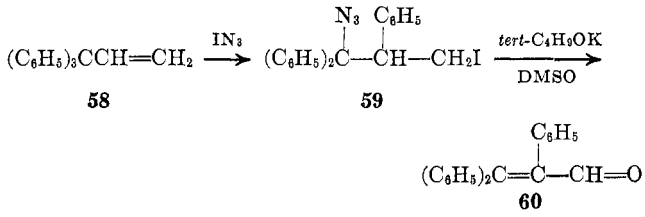


54 **55**
56 **57**

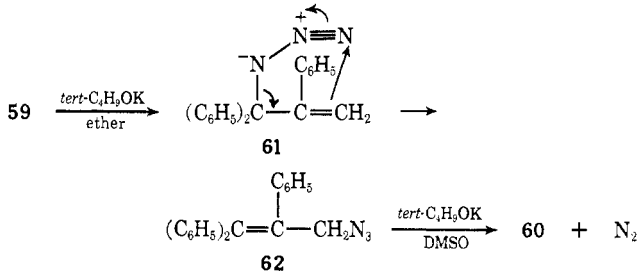
Unlike *tert*-butylethylene (**1**) in which no rearrangement was observed, tritylethylene (**58**) reacts with IN_3 to form exclusively **59**, the product of phenyl migration.[21] This is due to release of steric crowding as well as to the superior ability of the phenyl group to participate in the stabilization of a neighboring charge.

Dehydrohalogenation of **59** by means of *tert*-BuO^-K^+ in DMSO led to formation of **60**. We were able to show that azide **62** was the precurser of **60**. The reaction

(20) See, for instance, W. H. Mueller and P. E. Butler, *J. Amer. Chem. Soc.*, **90**, 2075 (1968).
(21) (a) A. Hassner and J. S. Teeter, *J. Org. Chem.*, **35**, 3397 (1970); (b) A. Hassner and J. S. Teeter, in press.

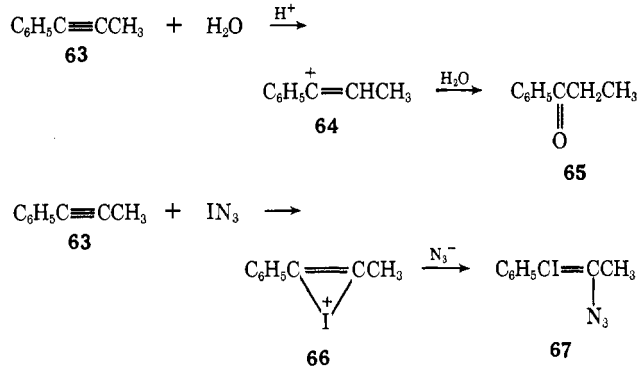


sequence involves an allyl azide rearrangement from **61** to **62**, which is presumably intramolecular.[22] One equivalent of N_2 was evolved during the conversion.

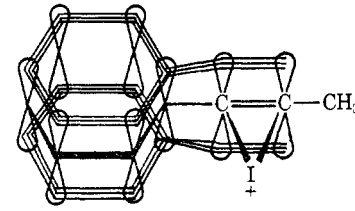


3,3-Diphenylpropene also adds IN_3 with complete rearrangement.

Additions to Triple Bonds. We considered it interesting to ascertain whether unsaturated three-membered iodonium ions (*e.g.*, **66**) are capable of existence. To this end we investigated the addition of IN_3 to acetylenes[23] and soon discovered that 1-phenylpropyne (**63**) reacted with IN_3 in the opposite regiochemical sense than on acid-catalyzed hydration (compare **65** to **67**).[24] Structure proof for **67** was furnished by its mass spectrum and by zinc reduction in aqueous acetic acid leading to phenylacetone exclusively and in high yield. It was shown on model systems that such reductions provide a marker for the position of the azide function in vinyl azides.



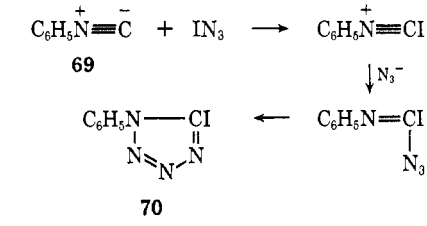
A rational explanation is that hydration involves protonation to a vinyl, benzylic cation, **64**, whereas IN_3 addition proceeds *via* the cyclic ion **66**. The opening of **66** by azide ions to yield **67** first appears regiochemically unusual. On closer inspection it becomes apparent that two cyclic ions **66** can exist, one in which the π orbitals of the double bond are parallel and overlapping with those of the benzene ring (see **68**) and one in which there is orbital overlap between the positively charged three-membered ring and the benzene ring (and hence the π orbitals of the aromatic ring are perpendicular to those of the olefinic double bond).



68

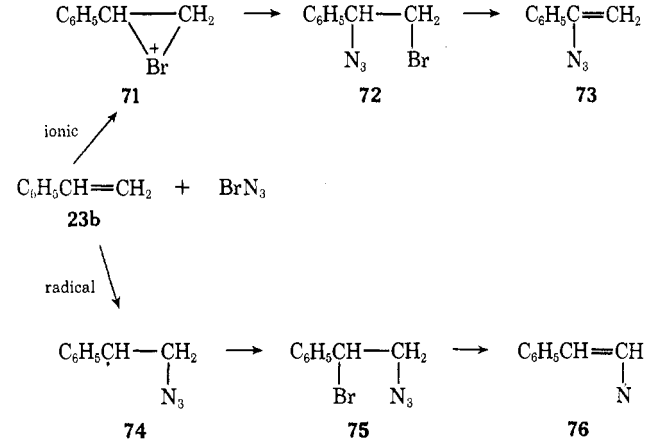
In the latter case as well as in the case of the open carbonium ion **64**, the positive charge at the α carbon is stabilized by delocalization into the benzene ring and the nucleophile attacks at this position. In **68**, on the other hand, the aromatic ring cannot contribute by resonance to stabilization of the iodonium ion and, since CH_3 can stabilize an incipient positive charge better by an inductive effect than C_6H_5, opening by the nucleophile occurs preferentially at the carbon α to methyl.

IN_3 obviously reacts by heterolytic cleavage during attack on the multiple bond. This is particularly noticeable in its behavior with isocyanides in which the carbon is known to be nucleophilic. Thus phenyl isocyanide (**69**) leads to 5-iodotetrazole **70** in high yield, undoubtedly by the reaction sequence shown below.[6]



Bromine Azide. Ionic *vs.* Free-Radical Additions

Since the electronegativity of Br and Cl is higher than that of I and probably also higher than that of the N_3 radical, we expected BrN_3 and/or ClN_3 to be capable of free-radical behavior toward olefins. It was gratifying to see these predictions come true. Thus in



the reaction of styrene with BrN_3 the regiochemistry of the products depended dramatically upon the polarity of the solvent.[7] In nitromethane the adduct was **72**,

(22) A. Gagneux, S. Winstein, and W. G. Young, *J. Amer. Chem. Soc.*, **82**, 5656 (1960).

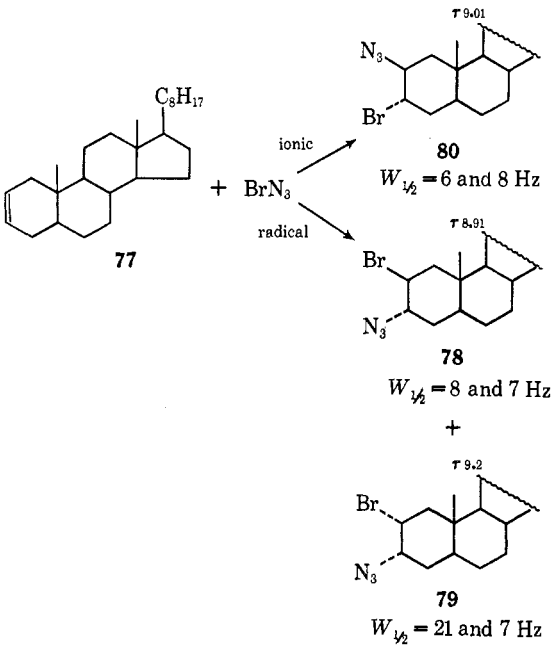
(23) A. Hassner, A. Friederang, and R. J. Isbister, *Tetrahedron Lett.*, 2939 (1969).

(24) D. S. Noyce and M. D. Schiavelli, *J. Org. Chem.*, **33**, 845 (1968).

resulting from ionic electrophilic attack of BrN_3 on the olefin, whereas in pentane even in the absence of free-radical initiators the reaction proceeded through attack of $N_3\cdot$ on the double bond to give exclusively the opposite regioisomer **75**. The structure of the ionic and free radical BrN_3 adducts was obvious from dehydrobromination to **73** and **76**, respectively.

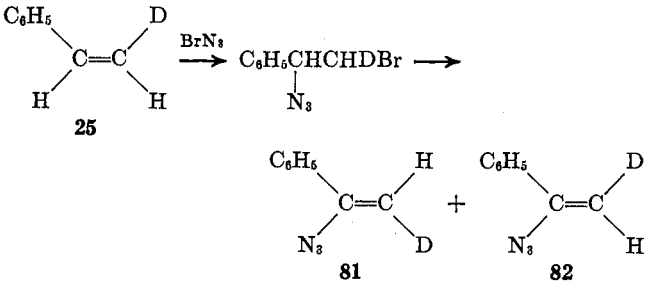
Using solvents of intermediate polarity such as methylene chloride or acetonitrile variable mixtures of the regioisomers **72** and **75** were obtained. The free-radical mechanism of addition was substantiated by the fact that the proportion of the ionic adduct **72** was increased in the dark or in the presence of oxygen (a free-radical inhibitor), whereas the proportion of **75** was increased in the presence of light or peroxides.

We found the free-radical addition to BrN_3 to be nonstereospecific; for instance, cyclohexene gave a mixture of *cis* and *trans* adducts. Similarly, 2-cholestene (**77**) reacted with BrN_3 under free-radical conditions to give two stereoisomers **78** and **79**. By contrast the ionic addition led solely to the diaxial adduct **80** ($W_{1/2}$ at C-2 and C-3 = 6 and 8 Hz), due to stereoelectronic influences in the opening of the three-membered-ring bromonium ion in the chair conformation of the cyclohexane ring.[7] The structures of isomers **78–80** were deduced in part from the chemical shift values of the C-19 methyl group and the half-width of the protons at C-2 and C_3 ($W_{1/2} < 12$ Hz for equatorial H's and >15 Hz for axial H's).[25]

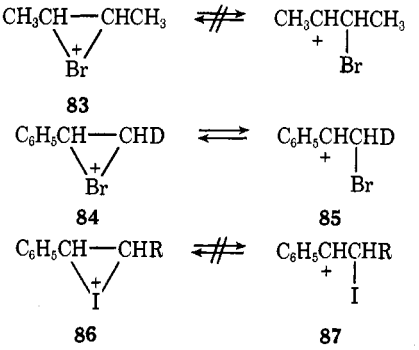


The ionic addition of BrN_3 occurs stereospecifically trans with alkyl-substituted olefins such as *cis*- and *trans*-2-butene. With *cis*-β-deuteriostyrene, however, we found a mixture of adducts as evidenced by the formation of a mixture of α-azido-β-deuteriostyrenes (**81** and **82**) on HBr elimination.[15] These results indicated that a three-membered-ring bromonium ion, **83**, is stable when flanked by alkyl groups, but that even one

(25) A. Hassner and C. H. Heathcock, *J. Org. Chem.*, **29**, 1350 (1964).

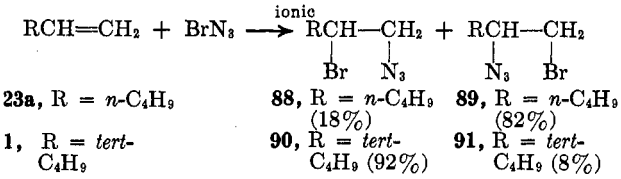


phenyl substituent is sufficient to cause equilibration of **84** to a benzyl cation **85**. As was shown above the corresponding phenyl-substituted iodonium ion **86** is

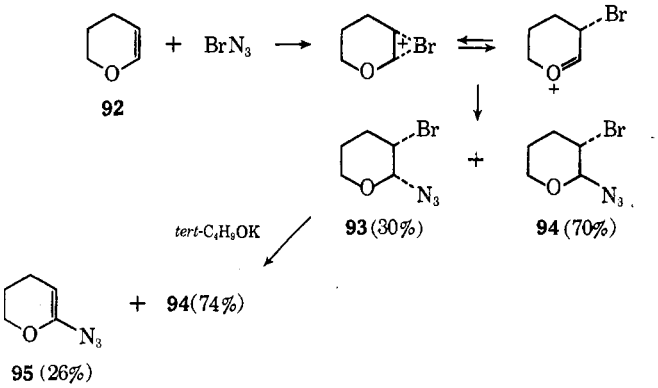


opened by azide ions before it can equilibrate to the carbonium ion **87**.

Further evidence that a three-membered-ring bromonium ion (*e.g.*, **83** or **84**) is slightly less stable, and consequently less discriminating in its reactions than the corresponding iodonium ion, is obtained from the reaction of BrN_3 with terminal olefins **23a** and **1**. The product ratios (**88**/**89** and **90**/**91**) were determined by gc and by nmr integration of the corresponding vinyl azide formed by potassium *tert*-butoxide induced elimination of HBr.

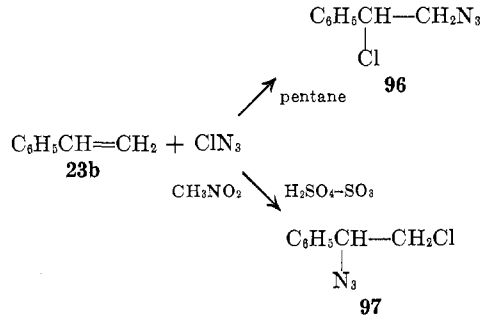


That HBr elimination occurs stereospecifically anti from bromine azide adducts, in the same way as HI elimination takes place from iodine azide adducts, is shown by the fact that the mixture of cis and trans adducts **93** and **94** obtained from dihydropyran **92** yields a mixture of unreacted **94** and vinyl azide **95**.[19]

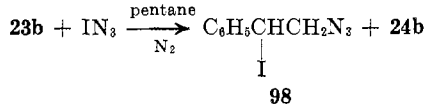


Chlorine Azide Additions

Recently Poutsma was able to show that chlorination of olefins proceeds by competing radical and ionic processes.[26] The ability of BrN_3 to react with olefins *via* two pathways prompted us to examine the behavior of chlorine azide under analogous conditions.[7] As expected, ClN_3 added to olefins primarily as a free-radical reagent providing a source of N_3 radicals. Thus in pentane or CH_2Cl_2, even in the presence of air, styrene furnished **96** as the sole product. In nitromethane in the presence of oxygen **96** was still formed in 17% yield, together with 48% of **97** and 23% of β-chlorostyrene. Under forcing conditions in the presence of fuming sulfuric acid a 92% yield of the ionic adduct **97** was obtained.



Even IN_3, which in acetonitrile reacts exclusively as an I^+ reagent, can be induced to react by an N_3 radical mechanism. For instance, in pentane and with N_2 purging, styrene (**23b**) gave the free radical adduct **98** in yields of up to 40%.[7]

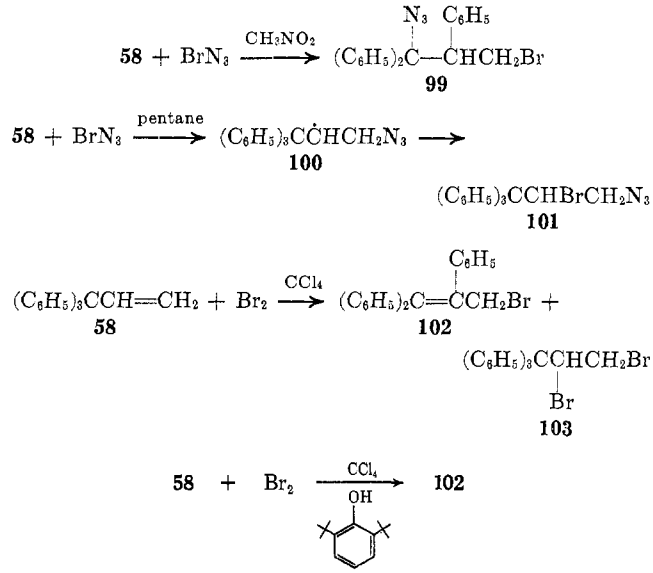


Conclusion

The addition of halogen azides to olefins provides a useful method for the stereospecific and regiospecific introduction of an azide function into organic molecules. The resulting β-haloalkyl azides serve as starting materials for vinyl azides, amines, amino ketones, azirines, aziridines, and other *N*-heterocycles. From the mechanistic point of view these reactions shed light on the behavior of three-membered-ring halonium ion intermediates and the electronic, steric, and conformational factors governing ionic as well as free-radical additions to olefins and acetylenes.

It is obvious that the addition of IN_3 to multiple bonds generally proceeds by an ionic mechanism, while ClN_3 adds predominantly by a free-radical pathway. BrN_3 is easily induced to react either by a free-radical or by an ionic pathway and even IN_3 or ClN_3 can add to olefins choosing a dual mechanism under forcing conditions. These results suggest that the mechanism of addition of bromine and of other halogens to unsaturated compounds may also be strongly affected by the polarity of the solvents and the reaction conditions employed, but that this is often not recognized. The halogen azides have the advantage that the reaction mechanism can usually be inferred from the observed regiochemistry, while in halogen additions this is not the case. An example is furnished below.

It has recently been reported[27] that 3,3,3-triphenylpropene (**58**) is brominated to yield a mixture of **102** and **103** and both products were presumed to arise from an ionic process. Our experience with this olefin indicated that ionic addition of IN_3 or BrN_3 leads exclusively to rearrangement (see **59** and **99**), whereas free-radical addition of BrN_3 led largely to an unrearranged adduct, **101**, indicating that the intermediate radical **100**, unlike the corresponding carbonium ion, is trapped efficiently by BrN_3 before it can rearrange.[21] Closer scrutiny of the bromination of **58** in the presence of free-radical inhibitors revealed that bromide **102** resulted from ionic bromination whereas dibromo adduct **103** was in fact a free-radical addition product.[21]



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(26) M. L. Poutsma, *J. Amer. Chem. Soc.*, **87**, 2161, 2172 (1965).

(27) R. O. C. Norman and C. B. Thomas, *J. Chem. Soc. B*, 598 (1967).