Orientation in 1,3-Dipolar Cycloadditions According to the Diradical Mechanism. Partial Formal Charges in the Linnett Structures of the Diradical Intermediates[1,2]

RAYMOND A. FIRESTONE

Synthetic Chemicals Department, Merck Sharp & Dohme Research Laboratories, Rahway, New Jersey 07065

The question of regioselectivity in 1,3-dipolar cycloadditions is taken up in detail from the viewpoints of both diradical and concerted mechanisms. The predominant unidirectionality of orientation exhibited by most 1,3 dipoles toward both electron-rich and electron-poor dipolarophiles is a natural consequence of the diradical mechanism but conflicts with the concerted one, as seen by analysis of both transition-state structure and prereaction complexes. Steric effects also favor the diradical theory. Linnett structures for the diradical intermediates possess partial formal charges, which account for (1) the nature of the favored diradicals, (2) the dual orientation of azides, and (3) the competition between cyclo and extended conformations of diradicals in reactions that exhibit concurrent cycloaddition and condensation with hydrogen transfer. Parallels with the Diels–Alder reaction and with free-radical additions are drawn.

Orientation, or regiospecificity, is an important criterion of mechanism in the field of cycloaddition reactions. For the Diels–Alder reaction, whatever its mechanism may be, it has long been recognized that the orientational phenomena are those that would be expected for a diradical mechanism.[3] On the other hand, regiospecificity in the closely related 1,3-dipolar cycloaddition reaction has been interpreted as favoring both diradical[4] and concerted[5-8] mechanisms. A detailed analysis of the latter field will be presented here, which will attempt to show that for this reaction, too, the orientational facts are in accord with the diradical mechanism.

The Concerted Mechanism.—In its simplest form, the concerted transition state for the cycloaddition of 1,3 dipole $a=b^+-c^-$ to dipolarophile $d=e$ is **1**, with the formation of the two new bonds equally well advanced and synchronized with the dissolution of the two old bonds. However, when the dipolarophile bears a substituent with appreciable conjugation energy, which is lost in the product, **1** implies that part of this energy is lost in the transition state, which would retard the reaction relative to one with an unsubstituted dipolarophile. Yet the opposite seems to be an invariable rule, *i.e.*, all substituents in the dipolarophile (relative to H) strongly accelerate 1,3-dipolar cycloadditions. For this reason, the concerted mechanism has been described as "concerted but not synchronous,"[5] with transition state **2** rather than **1**. The six electrons of interest in **2** move together but do not march precisely

in step, creating a surplus or deficiency of electrons in the dipolarophile which conjugates with the substituent

more strongly than did the original double bond. Control over orientation has been assigned[5] to two factors: (1) the σ-bond energy factor, active only when the two atoms d and e in the dipolarophile are different, and (2) steric effects. The first factor is not operative for $C=C$ and $C\equiv C$ dipolarophiles, which are the most numerous that have been studied, and will be the only types to be discussed herein; thus the σ-bond energy factor requires no further consideration. Steric effects will be discussed later on in the paper.

It is not possible to predict, for any 1,3-dipole, what sort of unbalanced charge distribution in **2** is preferred, but it is apparent that any particular 1,3-dipole will tend to prefer the same nonsynchronous pattern in all its reactions. This pattern should affect orientation by guiding the β carbon of a monosubstituted ethylene with an electron-withdrawing substituent to that end of the 1,3-dipole which tends to be electron-rich in the transition state, and the β carbon of an electron-rich olefin in the opposite fashion. Thus regiospecificity for electron-poor and electron-rich olefins should be opposite for each 1,3-dipole. The same remarks apply, incidentally, to the Diels–Alder reaction.[9]

There is another reason why olefins of opposite polarities should orient oppositely toward the same 1,3-dipole by a concerted mechanism. The approach of two polar molecules must be governed by electrostatic forces until the distance between them is small enough for covalent interaction to begin. In a concerted cycloaddition, the two partners must approach the transition state in a parallel position, with no solvent molecules in between. The electrostatic energy of this

(1) Application of the Linnett Electronic Theory to Organic Chemistry, Part V. Part IV: R. A. Firestone, *J. Org. Chem.*, **36**, 702 (1971).

(2) Presented in part at the IUPAC Symposium on Cycloadditions, Munich, Sept 1970.

(3) C. Walling, *J. Amer. Chem. Soc.*, **71**, 1930 (1949); E. C. Coyner and W. S. Hillman, *ibid.*, **71**, 324 (1949); G. Stork, S. S. Wagle, and P. C. Mukharji, *ibid.*, **75**, 3197 (1953); R. B. Woodward and T. J. Katz, *Tetrahedron*, **5**, 70 (1959).

(4) R. A. Firestone, *J. Org. Chem.*, **33**, 2285 (1968).

(5) R. Huisgen, *Angew. Chem., Int. Ed. Engl.*, **2**, 633 (1963).

(6) A. Eckell, R. Huisgen, R. Sustmann, G. Wallbillich, D. Grashey, and E. Spindler, *Chem. Ber.*, **100**, 2192 (1967).

(7) R. Huisgen, G. Szeimies, and L. Möbius, *ibid.*, **100**, 2494 (1967).
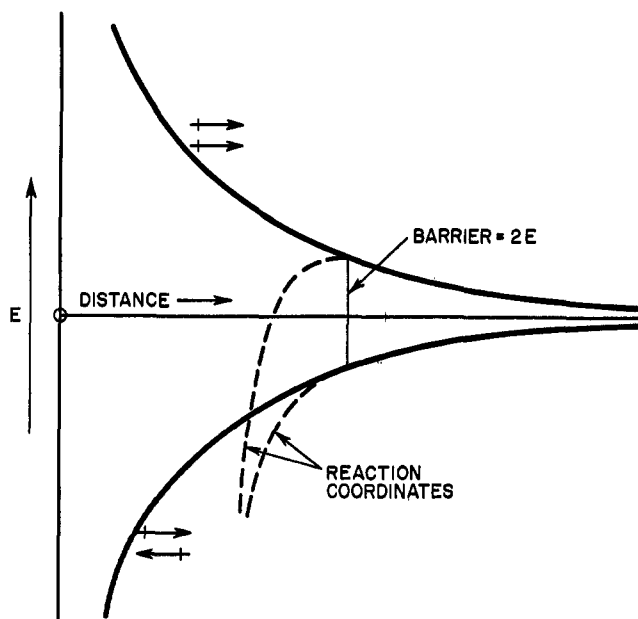
(8) R. Huisgen, *J. Org. Chem.*, **33**, 2291 (1968).

(9) Numerous theoretical studies based on the concerted mechanism support these statements. For the Diels–Alder reaction, where the substituents in diene and dienophile are of opposite polarities, preferential ortho-para orientation is predicted by PMO calculations.[10] However, exactly the same method predicts *meta orientation when both substituents are electron withdrawing*.[11] Another study reaches similar conclusions.[12] Only calculations aimed at predicting *which σ bond is formed first* have claimed complete success in accounting for orientation;[13] of course, this picture is identical with the diradical mechanism. For 1,3-dipolar cycloadditions, recent Hückel calculations of frontier orbital amplitudes, assuming a concerted mechanism, predict that all of a variety of common 1,3-dipoles should add in the opposite sense to electron-rich and electron-poor olefins.[14]

(10) J. Feuer, W. C. Herndon, and L. H. Hall, *Tetrahedron*, **24**, 2575 (1968).

(11) T. Inukai and T. Kojima, *J. Org. Chem.*, **36**, 924 (1971).

(12) J. Bertran, R. Carbo, and T. Moret, *An. Quim.*, **67**, 489 (1971).

(13) O. Eisenstein, J. Lefour, and N. T. Anh, *Chem. Commun.*, 969 (1971).

(14) Independent, unpublished study by Dr. B. G. Christensen of these laboratories.

Figure 1.—Parallel approach of dipoles.

array is expressed[15] by eq 1, where E is in kcal/mol, μ is in Debye units, and a is the distance of separation in

$$E = \pm\frac{14.4\mu_A\mu_B}{a^3} \tag{1}$$

Å. Interaction is favorable when the dipoles line up in antiparallel fashion, and unfavorable when they are parallel. Thus, the orientation of the 1,3-dipole toward the two classes of olefins should be opposite *as they approach* the transition state. Both cycloadditions are symmetry allowed, and consequently the transition state's orientation ought to be governed by the mode of approach.

It is recognized that, once covalent bond reorganization has become appreciable in the transition state, the dipole moments of the two partners prior to reaction are no longer of paramount importance. At this point, another factor *not yet identified* might conceivably cause certain transition states to be lower in energy than their orientational opposites, even in defiance of the electrostatically governed mode of approach. If such a factor exists, it is not orbital symmetry, nor, as will be seen later, is it steric. If no such factor exists, then the above prediction must hold.

Typical single bonds are about 1.5 Å in length, and since the Morse function that describes covalent bonding falls off with distance much faster than do electrostatic forces, which obey Coulomb's law, it is apparent that eq 1 governs the situation until the molecules are within a few Å of each other. As an example of the magnitude of the interaction, when $\mu_A = \mu_B = 3.5$ D and $a = 4$ Å, $E = 2.8$ kcal/mol, an appreciable number for a reaction whose activation energy is typically about 15 kcal/mol. Furthermore, for those examples in which the observed orientation is incorrect by this criterion, the energy difference, or "barrier," between the observed and the electrostatically preferred mode of approach is $2E$, or 5.5 kcal/mol,

(15) E. A. Moelwyn-Hughes, "Physical Chemistry," 2nd ed, Pergamon Press, Oxford, 1961, p 306. Strictly speaking, eq 1 applies only at the larger distances.

in the above example. Figure 1 expresses the situation graphically. An actual case will be presented subsequently.

The Diradical Mechanism.—In contrast with the concerted mechanism, the diradical mechanism predicts that the regiospecificity observed with both electron-poor and electron-rich olefins should be the same toward any given 1,3-dipole. Diradicals, as high-energy intermediates, lie close on the reaction coordinate to their transition states of formation, and therefore energy differences among them are taken as approximately equal to energy differences among the transition states. For any combination of 1,3-dipole and dipolarophile four diradical intermediates are possible. Only two of these need be considered when the dipolarophile is a monosubstituted carbon–carbon multiple bond, because relative to hydrogen all substituents stabilize a radical center, and the σ-bond energy factor is absent. In the generalized eq 2, the two possible regioisomeric products 5 and 6 arise from the diradicals 3 and 4, respectively. Diradicals 7 and 8 are obviously poorer than 3 and 4 because they do not utilize the radical-stabilizing power of the substituent X, and therefore need not be considered further.
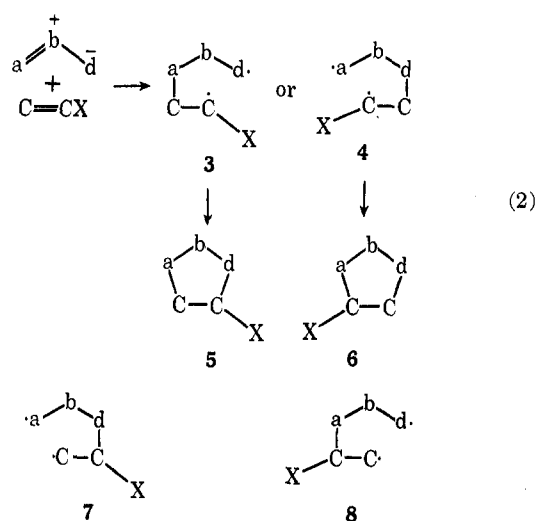
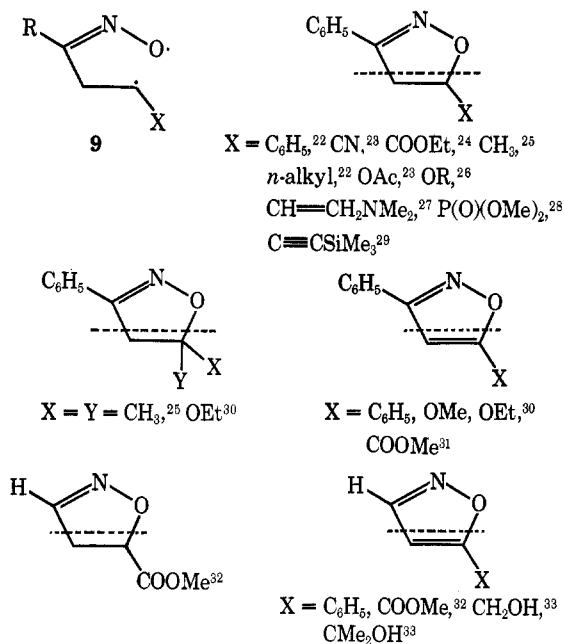For any individual 1,3-dipole, a preference for either 3 or 4 is expected, and this preference should be the same whether the substituent X in the dipolarophile is electron-attracting or electron-releasing. The preference need not be large, and it has been calculated[16] that, for most 1,3-dipoles, 3 and 4 differ little in bond energy, in accord with the fact that regioselectivity in 1,3-dipolar cycloadditions is seldom total. Nevertheless, the diradical mechanism clearly predicts that each 1,3-dipole should exhibit an orientational preference of the same kind for both electron-rich and electron-poor olefins. This prediction is exactly the opposite of that for the concerted mechanism.

Patterns of Orientation.—The most important fact concerning orientation in 1,3-dipolar cycloadditions is that there is a strong tendency for each 1,3-dipole (with one exception) to add in the same direction to both electron-rich and electron-poor olefins. This fact contradicts the concerted mechanism, and supports the diradical mechanism.

(16) R. A. Firestone, *J. Chem. Soc. A*, 1570 (1970).

Inasmuch as orientational patterns have already been discussed at length in a previous paper,[4] the remarks herein concerning this point will be kept to a minimum. The most extensively studied 1,3-dipoles are nitrile oxides, nitrile imines, nitrones, diazoalkanes, azomethine imines, sydnones, and azides. Only carbon–carbon dipolarophiles whose preferred modes of radical addition are unmistakable will be considered. In order to save space, for each 1,3-dipole only the most typical products will be shown, without equations; the dashed lines depict the mode of union of dipole and dipolarophile. Each regioisomer illustrated is the major one reported, and is frequently accompanied by lesser amounts of the other regioisomer.

The vast majority of adducts of nitrile oxides arise from diradicals of type **9**.[17] The variety of dipolarophiles which add in this fashion is exceptionally great, and only a small portion of the literature is summarized here.[22–33] Mesitonitrile oxide is a special case of great

interest which will be discussed separately, under "steric effects."

Nitrile imines have also been extensively studied, and their preferred orientation arises from diradicals **10**.[34–39]

10

X = COOR, C$_6$H$_5$, CN, alkyl,[34] NR$_2$,[6] OR,[35] C≡CSiMe$_3$,[29] P(O)(OMe)$_2$,[28] vinyl[34]

X = Y = CH$_3$,[36] C$_6$H$_5$,[37] OEt[34]
X = CH$_3$; Y = COOMe,[38] OEt[35]

X = C$_6$H$_5$, COOMe, CH(OPr)$_2$,[34] p-C$_6$H$_4$Y, where Y = NMe$_2$,[39] OMe, NO$_2$[37]

9

X = C$_6$H$_5$,[22] CN,[23] COOEt,[24] CH$_3$,[25] n-alkyl,[22] OAc,[23] OR,[26] CH=CH$_2$NMe$_2$,[27] P(O)(OMe)$_2$,[28] C≡CSiMe$_3$[29]

X = Y = CH$_3$,[25] OEt[30]

X = C$_6$H$_5$, OMe, OEt,[30] COOMe[31]

COOMe[32]

X = C$_6$H$_5$, COOMe,[32] CH$_2$OH,[33] CMe$_2$OH[33]

11

R, R' = C$_6$H$_5$, Alkyl
X = C$_6$H$_5$,[40] COOEt,[41] CONH$_2$,[42] CN,[41] 2-Py,[43] P(O)(OMe)$_2$,[28] C≡CSiMe$_3$,[29] CH$_2$OH,[41] OEt,[35] OBu,[43] alk,[24] N-pyrrolidinyl[44]

X = H; Y = CN, COOMe
X = CH$_3$; Y = COOMe

X = Y = OEt, C$_6$H$_5$[43]
X = CH$_3$; Y = C$_6$H$_5$,[43] COOMe[41]
X = C$_6$H$_5$; Y = N-pyrrolidinyl[46]

MeOOC

(17) Independent evidence for the existence of diradicals **9** are the observations of U-shaped Hammett plots for the addition of nitrile oxides to olefins CH$_2$=CHC$_6$H$_4$X[18] and acetylenes CH≡CC$_6$H$_4$X.[19-21] All X groups conjugated to an unsaturated radical center stabilize it relative to H. Substituents Y in YC$_6$H$_4$CNO, which are not conjugated with an unsaturated radical center in **9**, give normal Hammett plots stemming from purely ground-state effects.[18,19]

(18) A. Battaglia and A. Dondoni, *Ric. Sci.*, **38**, 201 (1968).

(19) A. Dondoni, *Tetrahedron Lett.*, 2397 (1967).

(20) P. Beltrame, C. Veglio, and M. Simonetta, *J. Chem. Soc. B*, 867 (1967).

(21) P. Beltrame, P. Sartirana, and C. Vintani, *ibid.*, 814 (1971).

(22) P. Grünanger, *Gazz. Chim. Ital.*, **84**, 359 (1954).

(23) G. Stagno d'Alcontres and P. Grünanger, *ibid.*, **88**, 741 (1950).

(24) R. Huisgen, *Angew. Chem., Int. Ed. Engl.*, **2**, 565 (1963).

(25) G. Stagno d'Alcontres, *Gazz. Chim. Ital.*, **82**, 627 (1952).

(26) R. Paul and S. Tchelitcheff, *Bull. Soc. Chim. Fr.*, 2215 (1962).

(27) P. Caramella and P. Bianchessi, *Tetrahedron*, **26**, 5773 (1970).

(28) I. G. Kolokol'tseva, V. N. Chistokletov, B. I. Ionin, and A. A. Petrov, *J. Gen. Chem. USSR*, **38**, 1203 (1968).

(29) I. G. Kolokol'tseva, V. N. Chistokletov, M. D. Stadnichuk, and A. A. Petrov, *ibid.*, **38**, 1771 (1968).

(30) P. Grünanger and M. R. Langella, *Gazz. Chim. Ital.*, **89**, 1784 (1959).
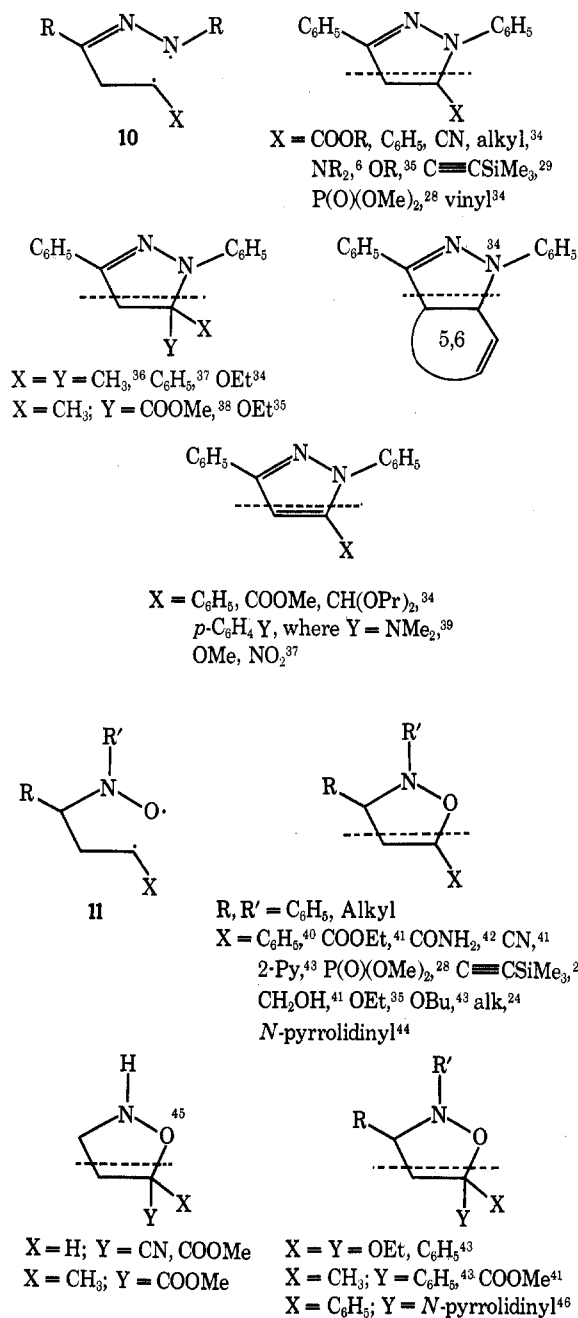
(31) M. Christl and R. Huisgen, *Tetrahedron Lett.*, 5209 (1968).

(32) R. Huisgen and M. Christl, *Angew. Chem., Int. Ed. Engl.*, **6**, 456 (1967).

(33) A. Quilico and G. Stagno d'Alcontres, *Gazz. Chim. Ital.*, **79**, 654, 703 (1949).

(34) R. Huisgen, M. Seidel, G. Wallbillich, and H. Knupfer, *Tetrahedron*, **17**, 3 (1962).

(35) R. Paul and S. Tchelitcheff, *Bull. Soc. Chim. Fr.*, 4179 (1967).

(36) R. Huisgen, H. Knupfer, R. Sustmann, G. Wallbillich, and V. Weberndorfer, *Chem. Ber.*, **100**, 1580 (1967).
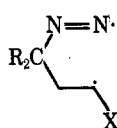
(37) J. S. Clovis, A. Eckell, R. Huisgen, R. Sustmann, G. Wallbillich, and V. Webernodorfer, *ibid.*, **100**, 1593 (1967).

(38) R. Huisgen, R. Sustmann, and G. Wallbillich, *ibid.*, **100**, 1786 (1967).

(39) S. Morrocchi, A. Ricca, and A. Zanarotti, *Tetrahedron Lett.*, 3215 (1970).
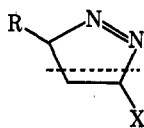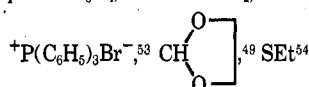
Nitrones react *via* diradicals of type 11.[40-47] Methyl propiolate does not fit the rule, but there are very few such exceptions in the nitrone field.

The best diradicals from diazoalkanes look like 12. Doubt has been cast on the ability of structures $RN_2\cdot$ to do anything except lose nitrogen,[8] but evidence from a variety of sources establishes that radicals $RN_2\cdot$, while unstable, can indeed enjoy finite existence.[48] Alkoxyacetylenes, alone in this large group, add in exceptional fashion.   (See ref 49–66.)

For azomethine imines, the best diradical is normally 13. At one time[4] it seemed that disobedience to the best diradical rule on the part of azomethine imines was widespread; however, their behavior appears less ambiguous in the light of recent evidence. Thus, diradical 13 prevails without exception with weakly substituted carbon, *i.e.*, when the carbon atom of the 1,3-dipole bears no strongly radical-stabilizing substituent.[67]


12   X = COOR,[24] CHO, Ac,[49] C_6H_5, m-$O_2NC_6H_4$,[50]
          p-$MeOC_6H_4$,[50] $CH=CH_2$,[51] $C\equiv CH$,[52]
          $^+P(C_6H_5)_3Br^-$,[53] CH(O–O),[49] SEt[54]

R = Ar; X = Ar[55]
R = X = COOMe[56]
R = CF_3; X = CF_3, CH_3[57]
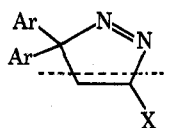
X = COOMe,[58] $^+P(C_6H_5)_3Br^-$[53]

OEt(i-Pr)
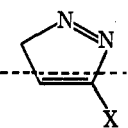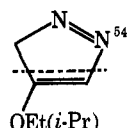
X = CH_2OH,[59] $SnEt_3$,[60] CHO, [61]
CH=CHOMe[62]
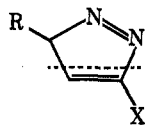
R = $CH_2=CH_2$; X = Ac, COC_6H_5[63]
R = CF_3; X = CF_3, Br[57]
R = COOEt; X = CHO[61]
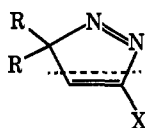
R = C_6H_5; X = CHO,[64] COOMe,[64,65] $C(CH_3)=CH_2$[66]
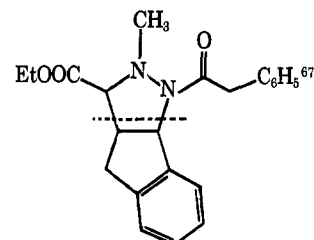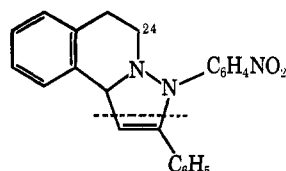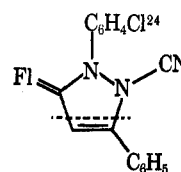R = CH_3; X = CH=CHOMe[62]
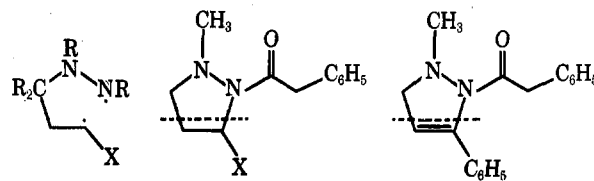
13   X = aryl, vinyl, COOEt, CN
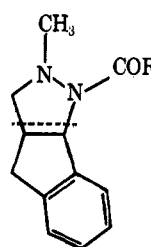
On the other hand, with strongly substituted carbon, orientations arising from diradical 14 account for a significant, though still minor, portion of the total.
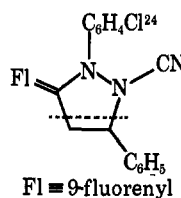
Fl = 9-fluorenyl

(40) R. Huisgen, R. Grashey, H. Hauck, and H. Seidl, *Chem. Ber.*, **101**, 2548 (1968).

(41) R. Huisgen, H. Hauck, R. Grashey, and H. Seidl, *ibid.*, **101**, 2568 (1968).

(42) B. G. Murray and A. F. Turner, *J. Chem. Soc. C*, 1338 (1966).

(43) R. Huisgen, R. Grashey, H. Seidl, and H. Hauck, *Chem. Ber.*, **101**, 2559 (1968).

(44) O. Tsuge, M. Tashiro, and Y. Nishihara, *J. Chem. Soc. Jap.*, **92**, 72 (1971).

(45) M. Ochiai, M. Obayashi, and K. Morita, *Tetrahedron*, **23**, 2641 (1967).

(46) O. Tsuge, M. Tashiro, and Y. Nishihara, *Tetrahedron Lett.*, 3769 (1967).

(47) H. Seidl, R. Huisgen, and R. Knorr, *Chem. Ber.*, **102**, 904 (1969).

(48) (a) S. Seltzer and F. T. Dunne, *J. Amer. Chem. Soc.*, **87**, 2628 (1965); (b) W. R. Roth and M. Martin, *Justus Liebigs Ann. Chem.*, **702**, 1 (1967); *Tetrahedron Lett.*, 4695 (1967); (c) W. A. Pryor and K. Smith, *J. Amer. Chem. Soc.*, **89**, 1741 (1967); **92**, 5403 (1970); (d) J. Hollaender and W. P. Neumann, *Angew. Chem., Int. Ed. Engl.*, **9**, 804 (1970); (e) P. B. Condit and R. G. Bergman, *Chem. Commun.*, **4** (1971); (f) N. A. Porter, M. E. Landis, and L. J. Marnett, *J. Amer. Chem. Soc.*, **93**, 795 (1971); (g) N. A. Porter and P. M. Iloff, Jr., *Chem. Commun.*, 1575 (1971).

(49) J. M. Stewart, C. Carlisle, K. Kern, and G. Lee, *J. Org. Chem.*, **35**, 2040 (1970).

(50) P. J. Kadaba and T. F. Kolturi, *J. Heterocycl. Chem.*, **6**, 829 (1969).

(51) E. Müller and O. Roser, *J. Prakt. Chem.*, **133**, 291 (1932).

(52) R. Kuhn and K. Henkel, *Justus Liebigs Ann. Chem.*, **545**, 279 (1941).

(53) E. E. Schweizer, C. S. Kim, and R. A. Jones, *Chem. Commun.*, **39**, 1584 (1970).

(54) S. H. Groen and J. F. Arens, *Recl. Trav. Chim. Pays-Bas*, **80**, 879 (1961).

(55) C. G. Overberger, N. Weinshenker, and J. Anselme, *J. Amer. Chem. Soc.*, **87**, 4119 (1965).

(56) E. Buchner, *Ber.*, **21**, 2637 (1888); **23**, 701 (1890); E. Buchner and A. Papendieck, *Justus Liebigs Ann. Chem.*, **273**, 232 (1893).

(57) J. H. Atherton and R. Fields, *J. Chem. Soc. C*, 1507 (1968).

(58) W. M. Jones, P. O. Sanderfer, and D. G. Baarda, *J. Org. Chem.*, **32**, 1367 (1967).

(59) R. G. Jones, *J. Amer. Chem. Soc.*, **71**, 3994 (1949).

(60) L. G. Sharanina, V. S. Zavgorodnyi, and A. A. Petrov, *J. Gen. Chem. USSR*, **38**, 1099 (1968).

(61) R. Hüttel, *Ber.*, **74**, 1680 (1941).

(62) M. Noel, Y. Vo-Quang, and L. Vo-Quang, *C. R. Acad. Sci.*, **270**, 80 (1970).

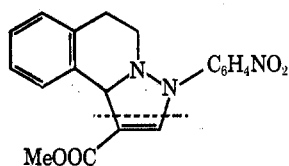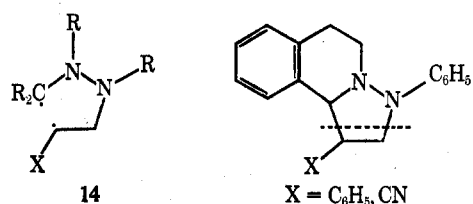(63) G. Manecke and H. U. Schenk, *Tetrahedron Lett.*, 617 (1969).

(64) R. Hüttel, J. Riedl, H. Martin, and K. Franke, *Chem. Ber.*, **93**, 1425 (1960).

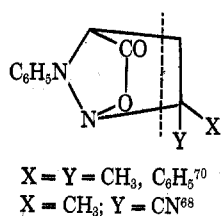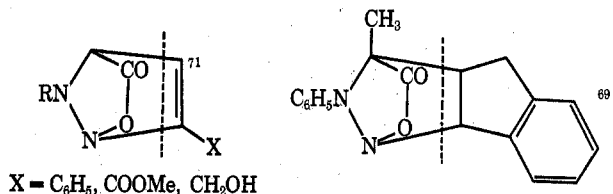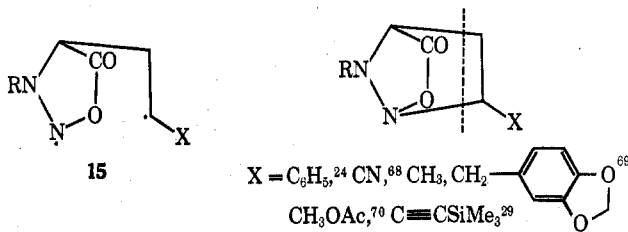(65) J. van Alphen, *Recl. Trav. Chim. Pays-Bas*, **62**, 485 (1943).

(66) L. Vo-Quang, *C. R. Acad. Sci.*, **266**, 642 (1968).

(67) W. Oppolzer, *Tetrahedron Lett.*, 2199 (1970).

Exceptions[24] are shown below.

14

X = C_6H_5, CN

Sydnones are azomethine imines which are unusually stable owing to the special circumstance of their aromaticity. They cycloadd according to diradical **15**,[68-71] the counterpart of **13**.

15

X = C_6H_5,[24] CN,[68] CH_3, CH_2—[69]

CH_3OAc,[70] C≡$CSiMe_3$[29]

X = C_6H_5, COOMe, CH_2OH

X = Y = CH_3, C_6H_5[70]

X = CH_3; Y = CN[68]

Up to this point, the unidirectionality of orientation exhibited by each individual 1,3-dipole clearly bespeaks a two-step mechanism with a diradical intermediate. Were the cycloadditions concerted, for each type the orientation would be incorrect for dipolarophiles of one or the other polarity. In azides, we now encounter for the first time a 1,3-dipole that orients in opposite fashion with olefins of opposite polarity. With electron-poor olefins, diradical **16** is preferred,[72,73] and with electron-rich olefins, diradical **17**.[74]

Nevertheless, even azides' orientations provide no support for the concerted mechanism, because not even half the dipolarophiles orient properly. Azides are polarized with the outer nitrogen negative,[24] and conse-

(68) R. Huisgen, R. Grashey, and H. Gotthardt, *Chem. Ber.*, **101**, 829 (1968).
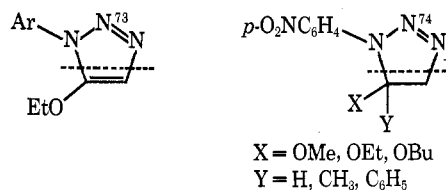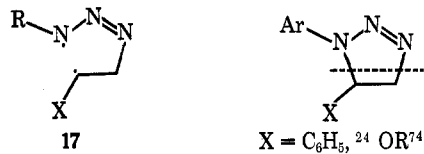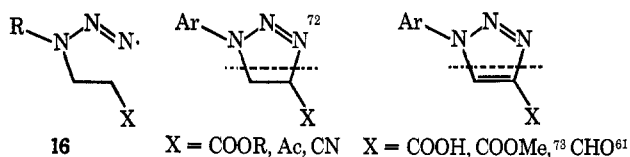(69) H. Gotthardt and R. Huisgen, *ibid.*, **101**, 552 (1968).
(70) R. Huisgen and H. Gotthardt, *ibid.*, **101**, 839 (1968).
(71) R. Huisgen, H. Gotthardt, and R. Grashey, *ibid.*, **101**, 536 (1968).
(72) R. Huisgen, G. Szeimies, and L. Möbius, *ibid.*, **99**, 475 (1966).
(73) R. Huisgen, R. Knorr, L. Möbius, and G. Szeimies, *ibid.*, **98**, 4014 (1965).
(74) R. Huisgen, L. Möbius, and G. Szeimies, *ibid.*, **98**, 1138 (1965).

16   X = COOR, Ac, CN   X = COOH, COOMe,[73] CHO[61]

17   X = C_6H_5,[24] OR[74]


X = OMe, OEt, OBu
Y = H, CH_3, C_6H_5

quently regioselectivity with both electron-rich and electron-poor olefins is incorrect for the concerted mechanism. Although at first glance the pattern seems no better for the diradical mechanism, it will be shown that diradicals actually work quite well for azides.

Electrostatic Forces and the Concerted Mechanism.—With the survey of orientational facts now completed, it is instructive to evaluate quantitatively the electrostatic "barrier," shown earlier to be $2E$ where E is defined by eq 1, for an actual case where the orientation is known to be incorrect for the concerted mechanism. The reaction of eq 3 occurs with a high degree of regiospecificity,[41] despite the antagonistic lineup of the molecular dipoles[75] as they approach. Table I lists the Coulombic interaction energies, or

TABLE I
COULOMBIC INTERACTIONS FOR EQUATION 3

Separation, Å	E, kcal/mol	Barrier ($2E$)
2	23.9	47.8
3	7.1	14.2
4	3.0	6.0
5	1.5	3.0
6	0.89	1.8
7	0.56	1.1
8	0.38	0.75

barrier, between the observed alignment and its opposite.

(3)
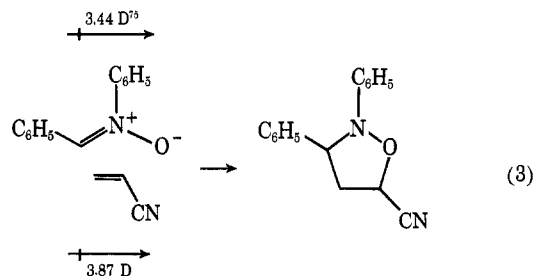
It is certain that for a concerted mechanism, in which the two partners must enter the transition state with their dipoles either parallel or antiparallel, before covalent interaction has begun *the 1,3-dipole and dipolar-*

(75) V. Baliah and V. Chandrasekharan, *Indian J. Chem.*, **8**, 1096 (1970).

ophile must be oriented in opposite fashion from that shown in eq 3. At this point—we know not precisely where, but 4–5 Å seems reasonable—a barrier must be invoked which raises the energy of the unobserved transition state by at least $2E$. The barrier is not orbital symmetry, since both orientations are symmetry allowed, and it is difficult to imagine the source of an effect so large in relation to the total activation energy, typically 16–18 kcal/mol for nitrones.

For a two-step mechanism, the electrostatic requirements for approach are much more relaxed, since not only may the alignment be less precise to form one new bond than two, but also, solvent molecules are not necessarily excluded from between the two ends of the developing diradical that are to later form the second bond. However, once the diradical has been formed, the radical centers are held rather close together, and electrostatic interactions between them become large enough to influence the formation of the second bond, as will be shown subsequently.

Regiospecificity in the Addition of Free Radicals.—The orientational rules found for the formation of diradicals from 1,3-dipoles also govern the addition of free radicals, which attack at the same site that dipolarophiles do in forming the first bond. In the examples below, to save space only the first intermediates are shown. (See ref 76–79.)


$$(C_6H_5)_3C\cdot + CH_2N_2 \longrightarrow (C_6H_5)_3CCH_2N_2\cdot{}^{77}$$

$$R\cdot + ArCNO \longrightarrow ArC\!=\!NO\cdot{}^{79}$$
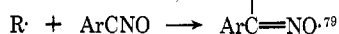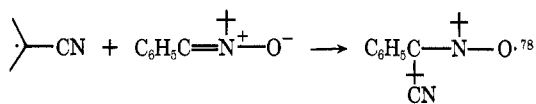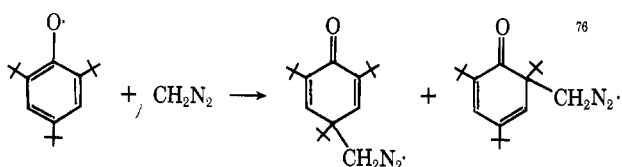
Interpretation of Regioselectivity in Cycloadditions.—Heretofore, orientational patterns have been presented as indicating that they fit the *idea* of best-diradical intermediates, and not the concerted mechanism. However, the diradical mechanism goes deeper than that, and accounts for the *nature* of the best diradicals as well.

The situation is simpler for the closely related Diels–Alder reaction. The predominant regioisomer from the reaction of a monosubstituted dienophile with 1- and 2-substituted butadienes is always the ortho and para isomer, respectively. This rule holds whether the activating groups in the diene and dienophile are of the same or the opposite electronic type. The nature
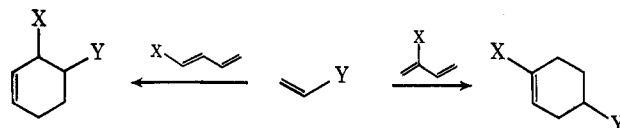

of the best diradical for each case is easily discerned here; **18** and **19** clearly account for the orientations.
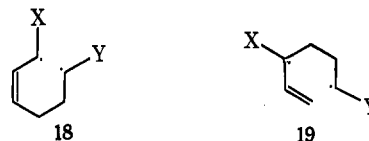
The observation is already well known.[3,80] If the mechanism were concerted, the orientation with any given diene should be opposite for dienophiles of opposite electronic type, for the reasons already given.[9]

The nature of the best diradicals for 1,3-dipolar cycloadditions is not as obvious owing to their more complicated electronic structures, but a method of analysis is now proposed.

Bond Energies of Regioisomeric Diradicals.—In a reaction involving an unstable intermediate, the transition state lies close to the intermediate on the reaction coordinate, and hence the activation energy will be but slightly greater than the difference in energy between the intermediate and reactants. For a wide variety of 1,3-dipolar cycloadditions, it has been shown that the bond energy changes from reactants and diradicals can be used to estimate activation energies to within a few kcal/mol.[16] Of importance to the question of orientation was the finding that, for many cases, the calculated change in bond energy is approximately the same for both regioisomeric diradicals. Thus, in eq 4, the losses in bond energy attending the formation of **20** and **21** are 14 and 15 kcal/mol, respectively. Within the accuracy of the method, these numbers are the same. A similar result was obtained with the majority of examples. Bond energy analysis thus accounts for the fact that *regioselectivity* rather than 100% *regiospecificity* is observed in most 1,3-dipolar cycloadditions, but does not yet explain the orientational patterns.
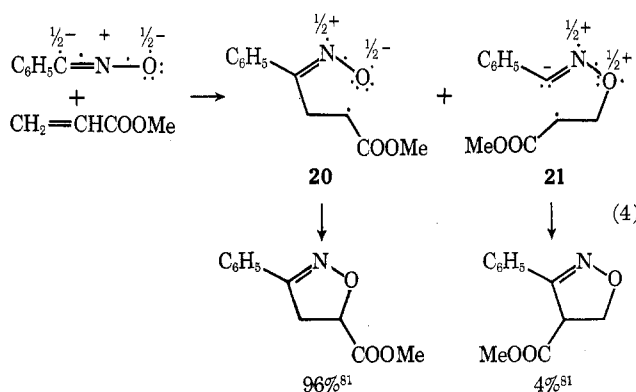
Partial Formal Charges in Diradicals.—In eq 4 the 1,3-dipole and diradicals are depicted as Linnett structures because the more conventional Lewis structures give erroneous results,[8] owing to their failure to take into account the stabilization of radical centers

(76) A. Rieker, R. Renner, and E. Müller, *Justus Liebigs Ann. Chem.*, **730**, 67 (1969).

(77) (a) W. Schlenk and C. Bonhardt, *ibid.*, **394**, 183 (1912); (b) E. Müller, A. Moosmayer, and C. Bonhardt, *Z. Naturforsch.*, **186**, 983 (1963); (c) D. B. Denney and N. F. Newman, *J. Amer. Chem. Soc.*, **89**, 4692 (1967).

(78) M. Iwamura and N. Inamoto, *Bull. Chem. Soc. Jap.*, **40**, 702, 703 (1967); **43**, 856, 860, 3638 (1970).

(79) (a) T. Caronna, A. Quilico, and F. Minisci, *Tetrahedron Lett.*, 3633 (1970); (b) B. C. Gilbert, V. Malatesta, and R. O. C. Norman, *J. Amer. Chem. Soc.*, **93**, 3290 (1971).

(80) J. Sauer, *Angew. Chem., Int. Ed. Engl.*, **6**, 16 (1967).

(81) M. Christl, Diploma Thesis, University of Munich, 1966.

adjacent to heteroatoms by partial bonding. Another attribute of the Linnett forms, heretofore ignored in our work but now to be featured, is their possession of partial formal charges. These exist at both ends of each diradical, but let us first focus our attention only on the end originating with the 1,3-dipole.

A simplified form of the analysis in ref 16 has been devised, which considers only those bond changes that are relevant to the question of orientation. Chart I illustrates the analysis for nitrile oxides.

CHART I

SIMPLIFIED ORIENTATION WITH NITRILE OXIDES[a]

C≡N	143	C≡N	143
N÷O	99	N÷O	99
C–C	83	C–O	86
5 pairs	20	4 pairs	16
C≡N÷	−3[b]	C≡N÷	−3[b]
	342		341
Advantage		1	

[a] In kcal/mol; for explanation see text. [b] L strain.

Diradicals **22** and **23** are the same as **20** and **21**, but with the elimination of all elements they hold in common. Thus the residue from the dipolarophile CH₂ĊHCOOMe is now depicted simply as D, and the phenyl group as R. The differences in electronic array are kept to the smallest possible compass, and only the central bonds and unshared electrons of the 1,3-dipoles are included in the analysis. Otherwise, the method is exactly the same as before. Bond energies are taken from standard sources, with odd-electron bond energies obtained by interpolation. Electron correlation is taken into account by listing, for each structure, the number of electrons not close-paired, an advantage of 4 kcal/mol per electron pair. L-Strain values are listed.

In the summation for each diradical, the *absolute* values obviously have no meaning, but the difference for each pair of regioisomers reflects their *relative* bond energies. These differences are the same as those derived from the more complicated analyses in ref 16 except that conjugation with R is neglected here. In all cases, whenever more than one Linnett structure could possibly be written, that structure was chosen which maximized the bond energy.

It is immediately seen that, although the bond energies of **22** and **23** are, within error, the same, the distribution of formal charges is not. They differ in that **22** has a half negative charge on oxygen while **23** has a full negative charge on carbon and a half positive charge on oxygen. These high values are doubtless mitigated by polarization of the valence shells, but the charge distribution unquestionably favors **22** over **23**, since oxygen, more electronegative than carbon, bears negative charge more easily and positive charge more reluctantly.

Thus diradical **22** is expected to prevail over **23**, in accord with observation. It will be seen that the interplay of formal charge distribution and electronegativity in the intermediate diradicals is the key to orientation for many 1,3-dipoles.

Chart II presents the results from simplified analyses

CHART II

SIMPLIFIED ORIENTATION WITH FOUR 1,3-DIPOLES

Nitrile imines

Nitrones

Azomethine imines

Diazoalkanes

of four other well-studied 1,3-dipoles. In the cases of nitrile imines and nitrones, the advantages in bond energy for the better diradicals are considered within the error of the method; for azomethine imines the advantage is considered of borderline significance; and for diazoalkanes, especially with nonconjugating R, significant. With each type of 1,3-dipole, the experimentally observed better diradical (**24, 26, 28**, and **30**) is that with the better charge distribution, in that the most electronegative atoms bear the most negative and the least positive charge. In addition, **28** has a slight, and **30** a significant, bond energy advantage over **29** and **31**.

The orientational patterns for the majority of 1,3-dipoles are thus seen to be explained by the diradical mechanism. The method of analysis, while not as simple as that for the Diels–Alder reaction shown earlier, is nevertheless consistent and unambiguous.

The only important 1,3-dipole whose orientation is not unidirectional is the azide function. Nevertheless, azides do fit the diradical mechanism (and not the concerted; *vide supra*). Chart III gives the results of

CHART III

SIMPLIFIED ORIENTATION WITH AZIDES

simplified analysis for azides. Both orientations have essentially the same bond energy, and since both terminal atoms are nitrogens, the electronegativity criterion cannot be used here, as with the other 1,3-dipoles. A minor distinction is that **33** has the greater

charge separation of the two,[82] which, other things being equal, should give an edge to **32**. However, extending our scrutiny backwards along the reaction coordinate to the transition states,[84] we find that electron-poor and electron-rich olefins give rise to quite different charge distributions. Chart IV depicts the

CHART IV

TRANSITION STATES FOR AZIDES

electron-poor olefins

34   **35**

electron-rich olefins

36   **37**
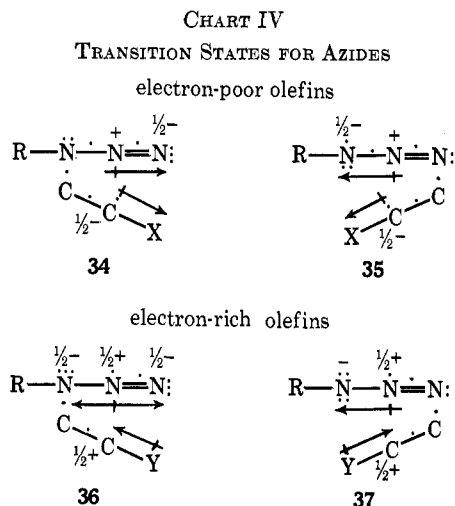
transition states for both orientations with each type of dipolarophile. All structures have been adjusted for the maximum possible bond energies. The arrows denote localized dipoles created by partial formal charges. It is assumed that electron-poor dipolarophiles prefer to be electrophilic in the transition state, reacting in the sense
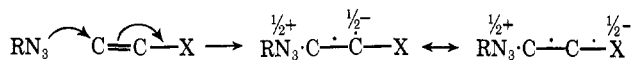
and that electron-rich dipolarophiles act as nucleophiles, *viz.*
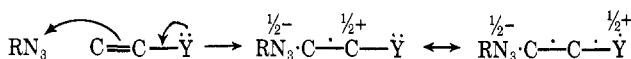
Electron-poor olefins give rise to transition states **34** and **35**, which have identical juxtapositions of localized dipoles. Therefore, the only remaining distinction between the regioisomeric diradicals **32** and **33** lies in their charge distributions, which, as observed earlier, favor **32**. The orientation of azides with electron-poor olefins, then, should fit in with diradical **16** as observed.

Electron-rich olefins, in contrast, lead to transition states **36** and **37**, whose localized dipoles face each other in markedly different ways. The electrostatic array in **37** is clearly lower in energy than that in **36**,[85] which might be sufficient to tip the balance toward the opposite orientation, represented by diradical **17** (or **33**). This is indeed the preferred diradical for electron-rich dipolarophiles.

(82) This greater charge separation is responsible for the fact that alkyl azides show greater regioselectivity than phenyl azide with electron-poor olefins.[83] Diradical **33** is less disfavored when R is phenyl because the inner nitrogen's negative charge can be better delocalized.

(83) W. Broeckx, N. Overbergh, C. Samyn, G. Smets, and G. L'abbe, *Tetrahedron,* **27**, 3527 (1971).

(84) More accurately, to the midpoints of the reaction coordinates. The true transition states lie farther along but before the diradical intermediates.

(85) For a similar example of conformational effects caused by the interaction of localized dipoles, see D. N. Harpp and J. G. Gleason, *J. Org. Chem.,* **36**, 1314 (1971).

If this explanation is correct, then the difference between **32** and **33** in charge distribution ought to cause a large difference in rates with olefins of opposite polarity when the group R is varied. In particular, electron-withdrawing substituents in R should promote reaction with electron-rich but not electron-poor dipolarophiles; or in other words, the reactivity of the azide should be most sensitive to olefin polarity when R is a good electron sink, and least when it is not.

These expectations are amply fulfilled, as shown in Table II. The diradical mechanism is supported in

TABLE II

SOME REACTION RATES WITH AZIDES[a]

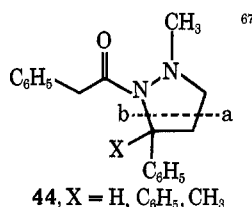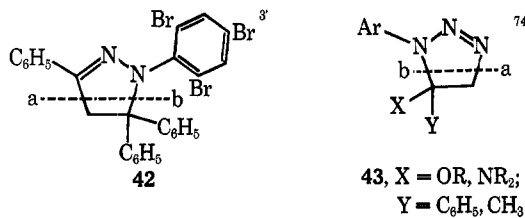|	Maleic anhydride	1-Pyrrolidino-cyclohexene	Relative rate, enamine/anhydride
p-MeOC$_6$H$_4$N$_3$ (**38**)	20.8	3.15×10^3	151
p-O$_2$NC$_6$H$_4$N$_3$ (**39**)	1.28	1.42×10^6	1.1×10^6
Rel rate, 38/39	16	1/450	
Hammett ρ	-1.1	2.54	

[a] $10^7 k_2$, benzene, 25°. See ref 7.

every detail by (1) the much greater sensitivity of **39** than **38** to type of dipolarophile, (2) greater sensitivity of electron-rich than electron-poor olefins to substitution in R, and (3) the very large difference in Hammett ρ constants between maleic anhydride and 1-pyrrolidino-cyclohexene. Although a difference in ρ might be anticipated for a concerted mechanism also, the observed difference is far too great. The facts summarized in Table II have heretofore never been satisfactorily explained.
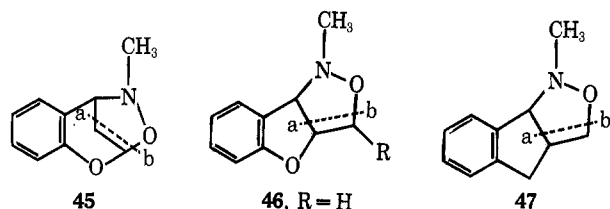
Steric Effects on Orientation.—One of the cornerstones of the interpretation of orientation according to the concerted mechanism has been steric effects.[5] Thus for example, **40** is obtained rather than **41**, supposedly because it is less crowded, and the two regioisomeric concerted transition states reflect in part **40**'s steric advantage.

40   **41**
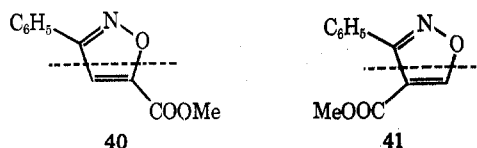
We shall present here only a few key examples which illustrate that steric effects actually favor the diradical, and not the concerted, mechanism. Compound **42** is highly crowded, and a concerted transition state with partial bonding at both a and b looks poorer than its regioisomer. There is no bar, however, to a transition state with only bond a being formed, leading to normal orientation *via* a diradical of type **10**. Exactly the same remarks apply to **43**. It embodies, in extreme form, all adducts of azides and electron-rich olefins, which now are seen to orient incorrectly for the concerted mechanism on both steric *and* electronic (*vide supra*) grounds. In **44** also, formation of unhindered bond a to the azomethine imine, leading to diradical **13**, is not inhibited because the more difficult linkage b is made only afterwards.

42

43, X = OR, NR$_2$; Y = C$_6$H$_5$, CH$_3$

44, X = H, C$_6$H$_5$, CH$_3$

48

49

but in a less dramatic way; the per cents of "normal" isomer formed with benzonitrile oxide, fulminic acid, and mesitonitrile oxide are 96, 100, and 93, respectively.[31]

Further examples of the preference of the more bulky mesityl group over phenyl for the sterically more demanding position in the adduct are provided in Table III.[88] It is clear that these facts can in no way be

Compound **45** illustrates another sort of steric effect. It is clearly more strained than its regioisomer **46**, the minor product, and indeed the opposite orientation **47** *is* found when the dipolarophile is weakly sub-
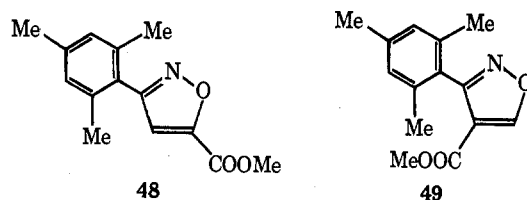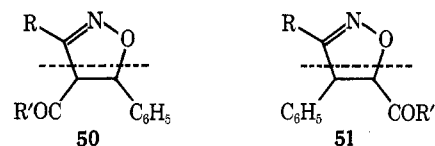
TABLE III

REGIOISOMERS FROM BENZO- AND MESITONITRILE OXIDES[a]

R	R'	50:51
Phenyl	CH$_3$	58:42
Mesityl	CH$_3$	28:72
Phenyl	α-C$_4$H$_3$S	44:56
Mesityl	α-C$_4$H$_3$S	14:86

[a] See ref 88.

45

46, R = H

47

accommodated by the concerted mechanism.

50

51

stituted.[86] Thus, the site of bond a in **45** is controlled by the strong substituent RO despite the strain created later in bond b, while the lack of a strong substituent in the latter case allows a to form at the other site, leading to **47**. In the absence of unusual influences, preferential formation of five-membered rather than six-membered rings is typical of free-radical cyclizations.[87] Failure to form **46** instead of **45** is thus incompatible with the concerted mechanism, but in harmony with the diradical mechanism.

We now come to the most striking example of steric effects. If the preference for **40** over **41** truly arises from steric interactions in concerted transition states, one would expect the degree of regiospecificity to diminish when the phenyl in benzonitrile oxide is replaced by a smaller group, and to increase when it is replaced by a larger one. *Yet exactly the opposite behavior is observed.* The regioselectivity for **40** is 72%, *i.e.*, **40:41** = 72:28. Replacement of the phenyl by the much smaller hydrogen *increases* the regioselectivity to 84%,[32] while replacement by the much larger mesityl group *lowers* it to 28%,[31] with the result that the sterically more crowded **49** is now favored over the "normal" isomer **48** by the ratio **49:48** = 72:28. Toward the dipolarophile acrylic ester, the situation is the same,

The diradical interpretation stems from the discussion given earlier about eq 4. The dipolarophile, *e.g.*, acrylic or propiolic ester, always prefers attack at the β carbon. The 1,3-dipole benzonitrile oxide prefers attack on carbon rather than oxygen (leading to a diradical of type **20**) but only by a small factor.[16] When the phenyl group grows to mesityl, steric hindrance to carbon attack increases, but not to oxygen attack, leading to an increase in the ratio **21:20**.

Example **53**[89] fits in with the foregoing discussion.[90]

53

(86) W. Oppolzer and K. Keller, *Tetrahedron Lett.*, 1117 (1970). When R is a radical-stabilizing substituent such as OR or COOEt, **46** becomes the major product.

(87) For just a few of the many reported examples, see (a) N. O. Brace, *J. Amer. Chem. Soc.*, **86**, 524 (1964); *J. Org. Chem.*, **31**, 2879 (1966); **32**, 2711 (1967); (b) C. Walling and M. S. Pearson, *J. Amer. Chem. Soc.*, **86**, 2262 (1964); (c) R. C. Lamb, J. G. Pacifici, and P. W. Ayers, *J. Org. Chem.*, **30**, 3099 (1965); (d) R. D. Rieke and N. A. Moore, *Tetrahedron Lett.*, 2035 (1969); (e) Y. L. Chow, R. A. Perry, B. C. Menon, and S. C. Chen, *Tetrahedron Lett.*, 1545 (1971); (f) P. Piccardi and M. Modena, *Chem. Commun.*, 1041 (1971). The preference for five-membered rings is kinetic, not thermodynamic: M. Julia, *Pure Appl. Chem.*, **15**, 167 (1967); M. Julia and M. Maumy, *Bull. Soc. Chim. Fr.*, 2415, 2427 (1969).

(88) C. J. Grundmann and P. Grünanger, "The Nitrile Oxides," Springer-Verlag, Heidelberg, 1971, p 104. We thank Professor Grünanger for a preprint of these data, and for several additional unpublished examples, all of a similar nature except one (in which phenyl and mesityl both give 87:13).
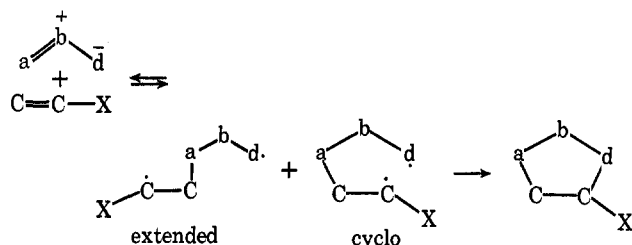
(89) E. Winterfeldt, W. Krohn, and H. Stracke, *Chem. Ber.*, **102**, 2346 (1969).

(90) Just as there exist analogies in free-radical chemistry for addition to 1,3-dipoles with the same orientation as that found for the favored diradicals in 1,3-dipolar cycloadditions (*vide supra*), an example has also been recently observed[91] of steric reversal of free-radical addition to *C*-phenyl-*N-tert*-butyl nitrone, in a manner exactly analogous to that described above for **48–53**. Thus, phenyl radical adds normally at carbon (hfc's, mT: a_N = 1.452, a_H = 0.221) but the hindered 2,4,6-trichlorophenyl radical adds principally at oxygen (minor isomer: a_N = 1.446, a_H = 0.227; major isomer: a_N = 1.436, a_H = 0.698). The esr of the latter radical is consistent with a highly delocalized benzyl radical.[92]

(91) R. A. W. Johnstone, A. F. Neville, and P. J. Russell, *J. Chem. Soc. B*, 1187 (1971); our interpretation, not the authors'.

(92) We thank Dr. Alan Douglas of these laboratories for his assistance in interpreting the esr spectra.

Partial Formal Charges and Diradical Conformation.—There remains to be discussed another aspect of the orientation of the 1,3-dipole toward the dipolarophile in the transition state, concerned with conformation rather than regioisomerism. An important corollary of the diradical theory is the possibility that the first new bond is formed at any dihedral angle between the reactants. The many possible conformations of the diradical are here idealized as the two extremes, the cyclo and extended conformations. Only the cyclo form may cyclize to product, and since single-

bond rotation is slower than either cyclization or reversion to reactants,[93] the extended form cannot achieve the cyclo form by rotation, but only by separation into reactants and then recombination. On this account it has heretofore been impossible to detect extended forms except through their effect on the entropy of activation (by lowering the per cent of effective collisions).[4] However, new discoveries, made since the first exposition of the diradical theory, have brought diradicals of extended form out of the shadow.[94]

It was first reported in 1969[95] that cycloaddition of nitrile oxides to arylacetylenes is accompanied by hydrogen transfer, forming oximes (eq 5). In corresponding fashion, nitrilimines afford hydrazones *via* hydrogen transfer, alongside normal cycloadducts (eq 6).[39] Ox-

RCNO + ArC≡CH →

RCNNR' + ArC≡CH →
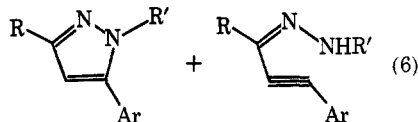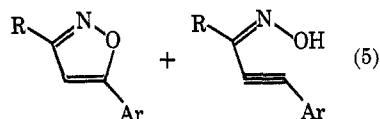
imes syn to the acetylene residue are formed exclusively.[96] Isoxazoles and oximes are formed independently (*i.e.*, not from each other) by second-order processes, both solvent independent and both with the same activation energy.[21,95,97,98] Hydrogen and deuterium are transferred at the same rate.[21]

(93) This is required by the stereospecificity of cycloadditions to cis and trans olefins.[4]

(94) Not all the authors cited in this connection have endorsed the diradical interpretation.

(95) S. Morrocchi, A. Ricca, A. Zanarotti, G. Bianchi, R. Gandolfi, and P. Grünanger, *Tetrahedron Lett.*, 3329 (1969).

(96) P. Grünanger, personal communication.

(97) A. Battaglia and A. Dondoni, *Tetrahedron Lett.*, 1221 (1970).

(98) A. Battaglia, A. Dondoni, and A. Mangini, *J. Chem. Soc. B*, 554 (1971).

These facts are best interpreted as arising from concurrent cyclization of cyclo diradicals (eq 2) and hydrogen transfer in extended diradicals 54 and 55[99], and establish the correctness of the diradical mechanism beyond a resonable doubt.[100]
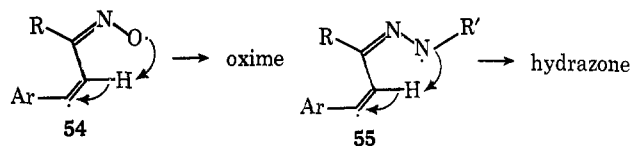

The competition between cyclo and extended diradicals, just as that between regioisomeric diradicals, is governed by partial formal charges. These were discussed earlier for the 1,3-dipoles' but not the dipolarophiles' portion of the diradicals. For an understanding of the latter, it is important to realize that even nominally neutral delocalized radicals have charge separation. This is not apparent from the Lewis structures, *e.g.*, 56 and 57, but becomes evident in the Linnett forms[101] 58, 59, and 60. Both canonical forms of the Lewis hybrids 56 and 57 have no charge
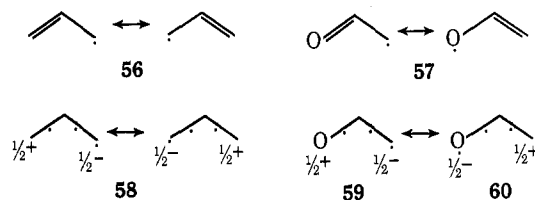
separation, and therefore even with unequal weighting of the forms of 57, *no extra polarity is imposed* by delocalization of the radical beyond that already inherent in the carbonyl group. On the other hand, it is obvious from the Linnett structures that, although 58 remains dipole-free overall,[102] 60 is better than 59, showing that delocalization definitely shifts negative charge toward carbonyl oxygen. Thus, delocalization of a radical into carbonyl, cyano, nitro, and the like imposes a partial positive charge on the radical center.

Stabilizing groups of the opposite type—amino, ether, halogen, etc.—impose partial negative charge on the radical center, as in 61.[105]
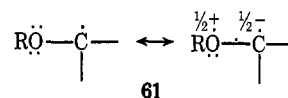
The complete array, then, of formal charges for diradicals arising from nitrile oxides and arylacetylenes bearing electron-withdrawing substituents X is summarized in 62, and with electron-releasing substituents

(99) The importance of hydrogen transfer in proving the existence of diradicals has also been recognized by Huisgen.[8]

(100) They do not thereby establish the incorrectness of the concerted mechanism, but the likelihood of two so dissimilar processes occurring simultaneously seems to us rather small.

(101) J. W. Linnett, *J. Amer. Chem. Soc.*, **83**, 2643 (1961); "The Electronic Structure of Molecules," Methuen, London, 1964.

(102) Yet the charges in forms **58** are not without consequence. They give rise to an excess of odd-electron spin on the terminal atoms, and an equal excess of the opposite spin on the central atom,[103] observed by esr.[104] The simple valence picture **56** shows none of this.

(103) D. M. Hirst and J. W. Linnett, *J. Chem. Soc.*, 1035 (1962); 1068 (1963).

(104) R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, **39**, 2147 (1963).

(105) R. A. Firestone, *Tetrahedron Lett.*, 971 (1968); *J. Org. Chem.*, **34**, 2621 (1969).

Y in **63**. For nitrile imines, the corresponding diradicals are **64** and **65**.
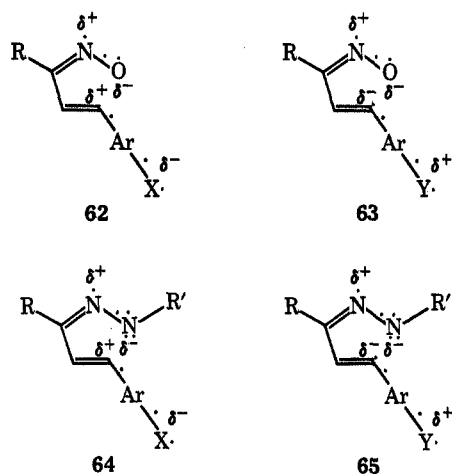
In **62** and **64**, the atoms which are to unite in cyclization bear opposite charges, while in **63** and **65** they bear like charges. A tendency is therefore anticipated for electron-withdrawing substituents to assist cyclization *via* cyclo forms **62** and **64**. Electron-releasing substituents, by creating repulsive interactions in **63** and **65**, must encourage reaction *via* extended diradicals such as **54** and **55**, *i.e.*, hydrogen transfer.[106]

The experimental results are in complete accord with this discussion. Tables IV[107] and V show data for nitrile oxides and nitrilimines which establish that both 1,3-dipoles exhibit the expected trend.

There is a clear shift toward hydrogen transfer and away from cyclization as the electron-donor power of the acetylenic substituent increases, as expected from the charge distribution in the diradicals **62–65**. Many more data, not reproduced here for lack of space, show exactly the same trend.[21,39,107] In addition, it is noteworthy that substituents in the nitrile oxide have, in contrast, almost no influence because their effect on the charge distribution in the diradicals is minor.

(106) We believe that this interpretation is sensibly the same as that offered in ref 21. Much the same argument was used by N. J. Turro and D. R. Morton, *J. Amer. Chem. Soc.*, **93**, 2569 (1971), to explain cyclization *vs.* cleavage ratios of various photochemically generated diradicals.

(107) S. Morrocchi, A. Ricca, A. Selva, and A. Zanarotti, *Atti Acad. Naz. Lincei*, **48**, 231 (1970), and personal communication from Dr. Ricca.

TABLE IV
PERCENTAGE OF OXIME FROM ARYLACETYLENES AND NITRILE OXIDES[a]

$$ArC{\equiv}CH \;+\; Ar'C{\equiv}NO \;\longrightarrow$$

Ar	Ar' p-MeOC$_6$N$_4$	C$_6$H$_5$	p-ClC$_6$N$_4$	p-O$_2$NC$_6$N$_4$
p-O$_2$NC$_6$H$_4$	0	0	0	*ca.* 5
p-ClC$_6$H$_4$	7	7	9	11
C$_6$H$_5$	10	12	15	18
p-MeOC$_6$H$_4$	24	28	32	34
p-Me$_2$NC$_6$H$_4$	52	53	65	74

[a] Oxime/(oxime + isoxazole) × 100. See ref 107.

TABLE V
PERCENTAGE OF HYDRAZONE FROM ARYLACETYLENES AND NITRILIMINES[a]

$$ArC{\equiv}CH \;+\; C_6H_5C{\equiv}NNC_6H_5 \;\longrightarrow$$

Ar	Hydrazone, %
p-O$_2$NC$_6$H$_4$	<17
C$_6$H$_5$	23
p-MeOC$_6$H$_4$	32
p-Me$_2$NC$_6$H$_4$	50

[a] Hydrazone/(hydrazone + pyrazole) × 100. See ref 39.

If the mechanism were concerted, one would have expected the results to be sensitive to substituents in both partners.

Conclusion.—The principal facts of orientation in 1,3-dipolar cycloadditions have been shown to be in accord with the diradical mechanism. Previous papers have dealt with energetics,[16] stereospecificity, solvent effects, and the question of acetylenic dipolarophiles.[4] Among these topics, the only one that is fully reconcilable with the concerted mechanism is stereospecificity, which is accommodated by both mechanisms. The weight of evidence at the present time therefore favors the diradical mechanism.