[Contribution No. 1675 from the Sterling Chemistry Laboratory, Yale University, New Haven, Conn.]

The Chemistry of Photodimers of Maleic and Fumaric Acid Derivatives. III. *cis,trans,cis*-1,2,3,4-Tetracyanocyclobutane; Possible Precursors for Tetramethylenecyclobutane

By G. W. Griffin, J. E. Basinski[1] and L. I. Peterson

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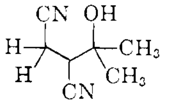
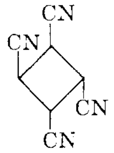
The photodimerization of fumaronitrile to tetracyanocyclobutane in the solid state has been studied and the stereochemistry of the dimer correlated with the crystal lattice structure of the monomer. The chemistry of the dimer has been investigated and a series of compounds derived from tetracyanocyclobutane have been synthesized including several precursors for tetramethylenecyclobutane.

As part of a continuing study concerned with establishing the role of olefin crystal lattice geometry in determining the stereochemical course of photochemical reactions we wish to report our results on the irradiation of fumaronitrile in the solid state and the chemical properties of the photodimer.[2,3] The choice of fumaronitrile as one of the initial substrates to be evaluated was based on the desire to synthesize 1,2,3,4-tetracyanocyclobutane which we felt would be an ideal precursor for tetramethylenecyclobutane. The latter, an unknown substance, is predicted on the basis of a simple molecular orbital treatment to possess a delocalization energy of 1.66β.[4]

The irradiation of fumaronitrile *in solution in acetone* had been reported to afford a 1:1 addition product of acetone and fumaronitrile (m.p. 40–40.4°) for which structure I was proposed.[5] No dimeric products were isolated, however.



I

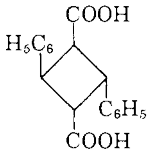


II

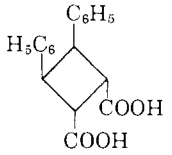
In contrast, the irradiation of fumaronitrile in the crystalline state provided a product which appeared to be a dimer of fumaronitrile on the basis of its infrared spectrum, ebullioscopic and mass spectral molecular weight, and elemental analysis. That this dimer possesses a cyclobutane structure II having *cis,trans,cis*-stereochemistry was established by the following transformations: acid hydrolysis[6] of II followed by esterification with diazomethane provided a product which was identical in all respects to the independently characterized *cis,trans,cis*-ester III.[2,3,7] Since III is known to be thermodynamically less stable than the all-*trans*-ester, it appears unlikely that acid-catalyzed isomerization has occurred during the hydrolysis reaction.[3,7a]

It is noteworthy that only one isomer (II) could be isolated from the dimerization reaction mixture, and that this isomer does not possess the most stable configuration, *i.e.*, *trans,trans,trans* stereochemistry. A similar behavior was noted and reported for the dimerization of dimethyl fumarate.[2] In the latter case it was concluded from X-ray crystallographic data that the stereochemistry of the dimer III was dictated by crystal lattice orientation, *i.e.*, that the stereochemistry of III could be rationalized by assuming direct bond formation between nearest neighbor molecules in the dimethyl fumarate crystal lattice.[8]

These data are in complete agreement with the results obtained by Schmidt[9,10] on the X-ray structure of the α- and β-crystal modifications of *trans*-cinnamic acid which dimerize to form α-truxillic (Va) and β-truxinic acid (Vb), respectively. Here again the crystal structure appears to be the controlling factor.



Va



Vb

A recent study of the crystal structure of fumaronitrile provides additional evidence that the stereochemistry of photodimerization reactions conducted in the solid state are controlled by crystal lattice factors. In the crystal lattice the molecules of fumaronitrile[11] are arranged as indicated in VI. This orientation is completely consistent with the formation of a dimer having the structure II

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[1] Part of the material presented in this paper has been taken from the thesis of J. E. Basinski, submitted in partial fulfillment of the requirements for the Ph.D. degree at Yale University.

[2] For the first paper in this series see, G. W. Griffin, A. F. Vellturo and K. Furukawa, *J. Am. Chem. Soc.*, **83**, 2725 (1961).

[3] For a preliminary report on this work see G. W. Griffin, J. E. Basinski and A. F. Vellturo, *Tetrahedron Letters*, **No. 3**, 13 (1960).

[4] J. D. Roberts, A. Streitwieser, Jr., and C. M. Regan, *J. Am. Chem. Soc.*, **74**, 4579 (1952).

[5] J. Jennen, *Bull. soc. chim. Belg.*, **46**, 258 (1931).

[6] A product (42%) resulting from partial hydrolysis of II and melting above 325° was assigned the *trans*-bis-imide structure IV on the basis of its infrared spectrum. An independent synthesis from XIII to be described later demonstrated that this is indeed the correct structure thus attesting further to the stereochemical similarity of the dimethyl fumarate and fumaronitrile dimers.

[7] R. Criegee and H. Höver, *Ber.*, **93**, 2521 (1960).

[7a] Note Added in Proof—A compound purported to have the cyclobutane structure II but possessing different physical and chemical properties was reported by T. Sadeh and A. Berger (*Bull. Res. Council of Israel*), **7A**, 98 (1958). Investigations in our laboratories carried out on a sample of their material demonstrate conclusively that it is in reality *trans*(?)-1,2,3-tricyanocyclopropane, m.p. 201°. Experimental details will be reported at a later date.

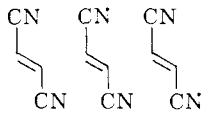
[8] I. E. Knaggs and K. Lonsdale, *J. Chem. Soc.*, 417 (1942).

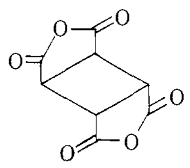
[9] G. M. Schmidt, *Acta Cryst.*, **10**, 793 (1957); Cohen and Schmidt Amsterdam Symposium on Reactivity of Solids, in press.

[10] G. M. Schmidt, private communication.

[11] B. Post, private communication. We wish to thank Professor Post for his data on the crystal structure of fumaronitrile prior to publication and Miss Sabina Sprague for assistance in building a three dimensional model of the unit cell.

provided bond formation occurs between nearest neighbor molecules and no major shifts in the relative positions of the atoms take place during the reaction.


VI


VII

Thus, all of the data accumulated up to the present time indicate a direct correlation between relative molecular orientations in the crystal lattice and product stereochemistry. The photodimerization of maleic anhydride[12] to the *trans*-bis-anhydride VII may well represent still another example. The relatively poor yields obtained with this olefin lead one to suspect that possibly the geometrical factors are not as favorable as they must be in cinnamic acids, dimethyl fumarate and to a lesser extent fumaronitrile. An X-ray diffraction study of maleic anhydride currently being conducted by Dr. G. M. J. Schmidt[10] should be revealing in this respect. An X-ray study is also in progress on a wide variety of related olefins which showed no tendency to dimerize under identical conditions. It is hoped that these data will be of help in establishing the minimal requirements (*i.e.*, intermolecular distances and orientations) necessary to permit dimerization to occur in such systems.

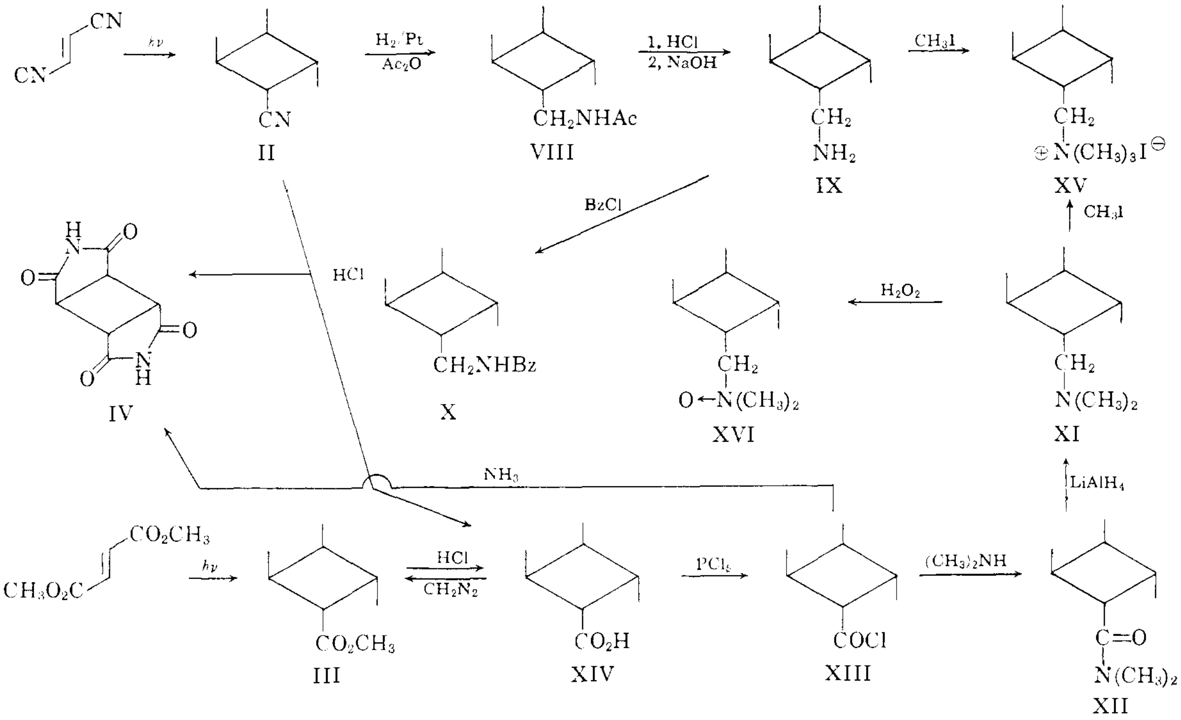


Fig. 1.

All attempts to reduce *cis,trans,cis*-1,2,3,4-tetracyanocyclobutane (II) directly to the corresponding tetraaminomethyl derivative with lithium aluminum hydride in a variety of solvents proved unrewarding—probably because of the low solubility of the polynitrile in compatible solvents. In contrast, catalytic reductive acetylation of II to *cis,trans,cis*-1,2,3,4-tetra-(acetamidomethyl)-cyclobutane (VIII) was achieved readily at room temperature in acetic anhydride using moderate pressures and platinum oxide as a catalyst. The infrared and n.m.r. spectra and elemental analysis are entirely consistent with the proposed structure. The high melting polyamide VIII (m.p. 278–279°) was subsequently hydrolyzed in acid and the solution then neutralized. After removal of water, the remaining solid was heated under vacuum in a sublimator. The white, extremely hygroscopic, crystalline product which sublimed had an elemental analysis and n.m.r. spectrum (D_2O) consistent with IX. Treatment of this amine with benzoyl chloride afforded a high melting solid (302–303°) whose elemental analysis and infrared spectrum is compatible with that expected for the tetrabenzamide derivative X.

An uncharacterized liquid possessing an infrared spectrum similar to that of VIII was also obtained in the reductive acetylation reaction. It may be an open chain by-product resulting from cleavage of the cyclobutane ring during hydrogenation.

The conversion of the tetraamine IX to 1,2,3,4-tetra-(dimethylaminomethyl)-cyclobutane (XI) by way of the Eschweiler–Clark method[13] was unsuccessful, apparently because of competing intramolecular reactions. However, XI was synthesized in high yield from the tetraamide XII by

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[12] G. W. Griffin and D. F. Veber, *J. Am. Chem. Soc.*, **82**, 6417 (1960).

[13] M. L. Moore, *Org. Reactions*, **5**, 301 (1949).

reduction with lithium aluminum hydride in the inverse manner using benzene and ether as a solvent system. The amide was obtained by conventional procedures from the acid chloride XIII which in turn was prepared from the tetraester III *via* the acid XIV as indicated in Fig. 1. The details of the preparation and reactions of this acid chloride as well as its *trans,trans,trans*-isomer will be reported elsewhere.

Oxidation of the tetraamine XI to the corresponding tetraamine oxide XVI was accomplished with 60% hydrogen peroxide. Although characterization of the free amine oxide was not attempted, a picrate formed readily and both its ultraviolet spectra and elemental analysis indicated that the complex consisted of four moles of picric acid per mole XVI.

Methylation of tetra-(dimethylaminomethyl)-cyclobutane (XI) with methyl iodide afforded a tetraquaternary salt XV whose infrared spectrum is identical in all respects to that observed for this material obtained by an alternate route from 1,2,3,4-tetra-(aminomethyl)-cyclobutane (IX). Thus, it is established conclusively that the cyclobutane ring is not opened during the reductive hydrogenation of II to VIII. Furthermore, since treatment with methanol has shown that the stereochemistry of the acid chloride XIII is the same as that of the tetracarbomethoxycyclobutane III and since there is no reason to suspect that isomerization would occur during the treatment with dimethylamine and subsequent reduction with lithium aluminum hydride, it appears that all of the compounds in Fig. 1 retain *cis,trans,cis*-stereochemistry.

The results of a study of the pyrolysis of the quaternary salt XV and the amine oxide XVI as well as the corresponding 1,2,3,4-tetraacetoxymethylcyclobutane[2] will be reported at a later date. The properties of 1,2,3,4-tetra-(aminomethyl)-cyclobutane as a complexing agent are currently under investigation.

Experimental[14]

***cis,trans,cis*-1,2,3,4-Tetracyanocyclobutane (II).**—Fumaronitrile, prepared according to the method of Mowry and Butler,[15] was deposited on the inside of a 1-l. graduated cylinder by evaporating an ethereal solution of the olefin under nitrogen. A Westinghouse 15T8 Germicidal Sterilamp was placed in the center of the tube and the outside of the cylinder was cooled in a water-bath (25–27°). After irradiation for one week, the brown residue was removed from the tube and extracted with hot ether to remove starting material. The insoluble residue was recrystallized from dry acetonitrile, yielding 2.1 g. (68% of converted material, 3.5% over-all) of a white crystalline solid, m.p. 250° dec.

Anal. Calcd. for $C_8H_4N_4$: C, 61.53; H, 2.58; N, 35.88; mol. wt., 156. Found: C, 61.38; H, 2.79; N, 35.88; mol. wt., 152.[16]

Hydrolysis of *cis,trans,cis*-1,2,3,4-Tetracyanocyclobutane (II).—Tetracyanocyclobutane (0.75 g., 0.0048 mole) was added to a solution of 20 ml. of glacial acetic acid and 1 ml. of concentrated hydrochloric acid. The suspension became clear after it had been heated and a solid slowly began to form. Most of the solvent was removed under vacuum, and the solid was collected on a filter (0.393 g.). Purification was effected by recrystallization of this material from acetone (m.p. 325°). On the basis of its infrared spectrum which showed the characteristic imide doublet at 5.65 and 5.88 μ (KBr) this product was assigned the bis-imide structure IV.

The filtrate from the hydrolysis reaction when treated with an ethereal solution of diazomethane deposited a precipitate which was removed by filtration. The filtrate was then concentrated further and a second solid precipitated (m.p. 144–145°) whose infrared spectrum and mixture melting point were identical with those of the methyl ester of *cis,trans,cis*-1,2,3,4-tetracarboxycyclobutane.

***cis,trans,cis*-1,2,3,4-Tetra-(acetamidomethyl)-cyclobutane (VIII).**—Tetracyanocyclobutane (8.0 g., 0.051 mole), acetic anhydride (150 ml.) and platinum oxide (0.70 g.) were placed in a hydrogenation flask under a pressure of 40 p.s.i. of hydrogen at a temperature of about 25°. The mixture was shaken for 1 week, after which time it was filtered, and 8.0 g. of crude product was collected. The solid was recrystallized from water, yielding 4.0 g. (23%) of a material (m.p. 278–279°) whose infrared and n.m.r. spectra are consistent with the amide structure.

Anal. Calcd. for $C_{16}H_{28}N_4O_4$: C, 56.45; H, 8.29; N, 16.46. Found: C, 56.49; H, 8.03; N, 16.42.

***cis,trans,cis*-1,2,3,4-Tetraaminomethylcyclobutane (IX).**—Tetraacetamidomethylcyclobutane (6.0 g., 0.018 mole) and 35 ml. of concentrated hydrochloric acid were heated for 3 hours. The solution was then evaporated to dryness. The residual material was sublimed at 80° (0.5 mm). The product first appeared as a liquid but crystallized when it was allowed to cool to room temperature. This amine is extremely hygroscopic and on exposure to moist air liquifies within minutes.

Anal. Calcd. for $C_8H_{20}N_4$: C, 55.77; H, 11.70; N, 32.53. Found: C, 55.55; H, 11.69; N, 32.33.

***cis,trans,cis*-1,2,3,4-Tetrabenzamidomethylcyclobutane (X).**—A sample of the tetraamine IX was dissolved in a 10% sodium hydroxide solution and benzoyl chloride was added. The precipitate which formed was collected on a filter and washed in turn with hot ethanol and water; m.p. 302–303°.

Anal. Calcd. for $C_{36}H_{36}N_4O_4$: C, 73.45; H, 6.16; N, 9.52. Found: C, 73.34; H, 6.11; N, 9.80.

Preparation of the Acid Chloride XIII and Dimethylamide XII of *cis,trans,cis*-1,2,3,4-Cyclobutanetetracarboxylic Acid (XIV).—A 5.0-g. (0.016 mole) sample of the acid chloride XIII (m.p. 76–77°, hexane) prepared by treating *cis,trans,-cis*-1,2,3,4-tetracarboxycyclobutane with phosphorus pentachloride was dissolved in 200 ml. of benzene. The resulting solution was stirred and treated with gaseous dimethylamine for a period of 4 hours. The reaction mixture was subsequently heated to boiling and filtered. The filtrate was then concentated under reduced pressure and afforded 5.1 g. (94%) of the crude amide. Purification was effected by recrystalization from ether-benzene; m.p. 194–195°.

Anal. Calcd. for $C_{16}H_{28}N_4O_4$: C, 56.45; H, 8.29; N, 16.46. Found: C, 56.69; H, 8.43; N, 16.49.

Preparation of *cis,trans,cis*-1,2,3,4-Tetra-(dimethylaminomethyl)-cyclobutane (XI).—To a stirred solution of 5.1 g. (0.015 mole) of the amide XII in a mixture of 100 ml. of ether and 100 ml. of benzene was added 1.7 g. (0.045 mole) of lithium aluminum hydride in the inverse manner. The addition was accomplished by extracting the reducing agent from a Soxhlet thimble with the refluxing solvent. After extraction was complete the reaction mixture was heated under reflux for an additional hour and then cautiously decomposed with 3 ml. of water followed by 35 ml. of a 20% sodium hydroxide solution. The organic layer was subsequently decanted and the aqueous layer extracted three times with ether. After the combined organic layers were dried over Drierite, the volatile solvents were removed under reduced pressure and the residual oil was distilled, b.p. 110–112° (0.05 mm.). The colorless product solidified on standing; 3.1 g. (74%). The infrared spectrum as determined in carbon tetrachloride had bands at the following wave lengths (μ); 3.36(s), 3.39(s), 3.49(s), 6.88(s) 6.95(m), 7.93(m), 9.62(s) and 9.76(s).

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[14] All boiling points and melting points are uncorrected. Analyses were performed by Schwarzkopf Microanalytical Laboratories, Woodside 77, N. Y.

[15] D. T. Mowry and J. M. Butler, *Org. Syntheses*, **30**, 46 (1950).

[16] This ebullioscopic measurement was made by Geller Laboratories, Bardonia, N. Y. An ebullioscopic constant of 46.62/g. was employed for acetonitrile, the solvent, and was obtained using phenanthrene as a reference compound.

Anal. Calcd. for $C_{16}H_{46}N_4$: C, 67.55; H, 12.76; N, 19.69; mol. wt., 284. Found: C, 67.76; H, 12.80; N, 19.80; mol. wt. (Signer–Barger in 2-butanone as a solvent), 270.

Exhaustive Methylation of *cis,trans,cis*-1,2,3,4-Tetra-(aminomethyl)-cyclobutane (IX) and *cis,trans,cis*-1,2,3,4-Tetra-(dimethylaminomethyl)-cyclobutane (XI).—A solution of 4.0 g. (0.028 mole) of methyl iodide and 1.0 g. (0.0035 mole) of dimethylaminomethylcyclobutane (XI) in 50 ml. of anhydrous methanol was heated under reflux overnight. The reaction mixture was then cooled and the product which deposited (2.4 g.) was collected on a filter and subsequently recrystallized from water; 2.2 g. (74%).

The infrared spectrum (KBr) had significant bands at the following wave lengths (μ); 3.32(m), 3.41(w), 6.80(s), 7.14(w), 10.50(m) and 11.23(m). It is identical in all respects to the infrared spectrum of the product obtained by exhaustive methylation of *cis,trans,cis*-1,2,3,4-tetra-(aminomethyl)-cyclobutane (IX).

Anal. Calcd. for $C_{20}H_{48}N_4I_4$: C, 28.18; H, 5.68; N, 6.58. Found: C, 28.19; H, 6.00; N, 6.29.

Peroxidation of *cis,trans,cis*-1,2,3,4-Tetra-(dimethylaminomethyl)-cyclobutane (XI) to the Amine Oxide XVI.—To a cooled and well stirred 60% solution of hydrogen peroxide was added 4.0 g. (0.012 mole) of 1,2,3,4-tetra-(dimethylaminomethyl)-cyclobutane. After 6 hours the reaction mixture was allowed to warm to room temperature and stand overnight. The mixture was then heated with a small amount of platinum-on-charcoal to decompose the excess hydrogen peroxide. The aqueous solution at this stage was neutral to phenophthalein indicating complete oxidation had occurred. Although the free amine oxide was not isolated, a picrate formed in the usual manner melted at 219–220° and from the elemental analysis and ultraviolet spectrum ($\lambda_{max}^{H_2O}$ 354, ϵ 59,000) the complex appeared to consist of four moles of picric acid per mole of XVI.

Anal. Calcd. for $C_{40}H_{44}O_{32}N_{16}$: C, 37.98; H, 3.83; N, 17.72. Found: C, 37.99; H, 4.11; N, 17.72, 17.52.

Preparation of the Bis-imide IV of *cis,trans,cis*-1,2,3,4-Cyclobutanetetracarboxylic Acid (XIV).—Three grams (0.01) mole of the tetraacid chloride XIII in 150 ml. of benzene was treated with gaseous ammonia. The reaction mixture was filtered and the white solid collected. Since the product was intractable, an elemental analysis was not obtained. But the infrared spectrum (KBr) which possessed characteristic imide bands at 2.96(m), 3.19(m), 3.28(m), 5.64(m), 5.86(s), 7.40(m), 7.69(w), 8.25(m), 8.51(m) and 10.04(m) μ was shown to be identical to the partial hydrolysis product from the tetranitrile II.

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[CONTRIBUTION NO. 2717 FROM THE GATES AND CRELLIN LABORATORIES OF CHEMISTRY, CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIF.]

The Triplet State of Methylene in Solution[1]

BY KARL R. KOPECKY,[2] GEORGE S. HAMMOND AND PETER A. LEERMAKERS[3]

RECEIVED OCTOBER 7, 1961

Diazomethane has been decomposed to methylene under a variety of conditions. The decomposition photosensitized by benzophenone yields triplet methylene which adds to *cis*- and *trans*-2-butene in a non-stereospecific manner. Methylene from the decomposition of diazomethane catalyzed by copper powder or by ferric dipivaloylmethide adds to *cis*- and *trans*-2-butene in a stereospecific manner. No insertion products are found in these reactions. Pyrolysis of diazomethane at 265° yields methylene which attacks cyclohexene and 2,2,4-trimethylpentane to give product ratios very similar to those from direct photolysis.

Introduction

Hantzsch[4] first noticed that a solution of diazomethane was rapidly decolorized on standing in sunlight, and Meerwein[5] first studied the photolysis of diazomethane in solution. However, it was the discovery by Doering[6] of the indiscriminate action of methylene produced by the photolysis of diazomethane which spurred the activity in this field in recent years.[7] The quantum state of the nonbonding electrons of methylene soon became a subject of inquiry.[8] Skell[8a,b] suggested that singlet methylene should react in a stereospecific manner with olefins, whereas triplet methylene should not, and therefore assigned the singlet state to methylene produced from photolysis of diazomethane on the basis of the stereospecificity of its addition to *cis*- and *trans*-2-butene. Hertzberg[8c] reported spectroscopic evidence that the vapor phase photolysis of diazomethane produces singlet methylene that decays to a triplet state in the presence of high pressures of inert gas. This result indicates the ground state of methylene must be the triplet state. Frey[8e] has obtained chemical evidence for the singlet–triplet decay of methylene in the gas phase in the presence of high pressures of argon and has shown that triplet methylene indeed reacts with *cis*-2-butene in a non-stereospecific manner.

Singlet–triplet decay of methylene has not yet been observed in solution because of the extreme reactivity of methylene. Methylene in solution inserted randomly between the primary, secondary and tertiary carbon–hydrogen bonds of an alkane.[6,9] The insertion reaction has been shown to be inter- as well as intramolecularly random.[9b] Singlet methylene must then react on one of the first collisions with a substrate, whereas the singlet–triplet decay requires numerous inert collisions.[8e]

Rabinowitch[8f] has thermally decomposed diazomethane in the presence of *cis*-2-butene. The re-

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[1] K. R. Kopecky, G. S. Hammond and P. A. Leermakers, *J. Am. Chem. Soc.*, **83**, 2397 (1961).

[2] U. S. Public Health Service Postdoctoral Fellow, 1959–1961.

[3] National Science Foundation Predoctoral Fellow, 1958–1961.

[4] A. Hantzsch and M. Lehman, *Ber.*, **34**, 2506 (1901).

[5] H. Meerwein, H. Rathjen and H. Werner, *ibid.*, **75**, 1610 (1942).

[6] W. v. E. Doering, R. G. Buttery, R. G. Laughlin and H. Chandhuri, *J. Am. Chem. Soc.*, **78**, 3224 (1956).

[7] For recent reviews on the chemistry of carbenes see (a) W. Kirmse, *Angew. Chem.*, **71**, 537 (1959); (b) **73**, 161 (1961).

[8] (a) P. S. Skell and R. C. Woodworth, *J. Am. Chem. Soc.*, **78**, 4496 (1956); (b) R. C. Woodworth and P. S. Skell, *ibid.*, **81**, 3383 (1959); (c) G. Hertzberg and J. Shoosmith, *Nature*, **183**, 1801 (1959); (d) F. A. L. Anet, R. F. W. Bader and A. M. Van der Auwers, *J. Am. Chem. Soc.*, **82**, 3217 (1960); (e) H. M. Frey, *ibid.*, **82**, 5947 (1960); (f) B. S. Rabinowitch and D. W. Setser, *ibid.*, **83**, 750 (1961).

[9] (a) D. B. Richardson, M. C. Simmons and I. Dvoretzky, *ibid.*, **82**, 5001 (1960); (b) **83**, 1934 (1961).