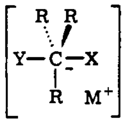
Communications to the Editor

Quest for an Observable Model for the S_N2 Transition State. Pentavalent Pentacoordinate Carbon

Sir:

Organic chemists have for years[1] been intrigued with the possibility that the trigonal-bipyramidal (TBP) geometry about carbon at the midpoint of the Walden inversion process of the S_N2 reaction (**1**) represents a metastable intermediate, rather than the transition state for the reaction.[2] Recent experimental studies of nucleophilic displacements in the gas phase[3] and several theoretical studies[4] agree that no such intermediate is likely in simple displacements such as those of halide ions on methyl halides. We describe the direct observation of trifluoromethanesulfonate (TfO$^-$) salts of dicationic species for which we postulate[5] structures **2a–c**—compounds with structural features designed[5] to stabilize the bonding about the postulated pentavalent TBP carbon. All organic compounds previously reported have contained only carbon atoms in valence states four or less (radicals, carbenes). Recent attempts[6] to gain evidence requiring the *intermediacy* of pentavalent carbon species[7] have not been successful, even though structural features thought to be favorable to such intermediates have been incorporated into the molecules studied.



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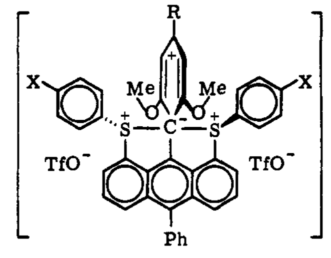
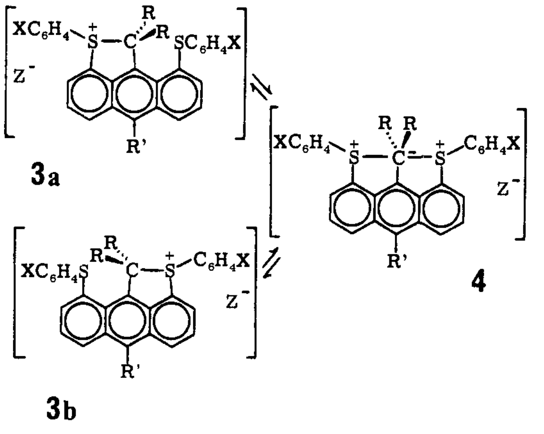


2a (X = CH$_3$, R = H)
b (X = CH$_3$, R = t-Bu)
c (X = F, R = H)

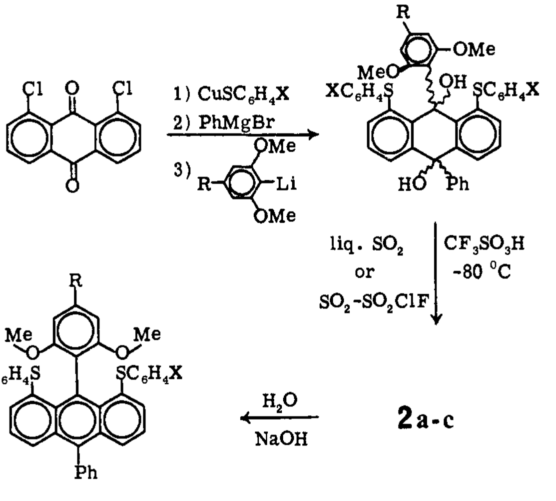
The intramolecular process interconverting **3a** and **3b**, the "bell-clapper" rearrangement, was shown[6a] to have characteristics of an S_N2 displacement with $\Delta H^\ddagger$ of only ~10 kcal/mol in the most favorable cases, those in which X is electron withdrawing.



Symmetrical structure **4** is either a transition state or possibly (no direct evidence for this was obtained) a metastable intermediate. It is favored relative to its unsymmetrical isomers, **3**, by (a) its two five-membered rings, which link apical with equatorial positions;[5b] (b) its benzoannelation, which maintains both sulfurs closely juxtaposed to the central carbon;[5b] and (c) positive charge on the apical sulfurs, which enhances the effective electronegativity of these apical ligands and stabilizes the hypervalent[8] TBP species.[5b]

In addition to these structural features, common to **2a–c** and **4**, the dications (**2a–c**) have two π-acceptor equatorial ligands. The acceptor pentadienyl cation system of **2** bridges two equatorial positions in a six-membered ring (the appropriate ring size to accommodate the 120° angle expected between equatorial bonds).[9] It is known[10] that π-acceptor equatorial ligands stabilize certain sulfuranes. The transition states for S_N2 reactions of phenacyl halides have also been shown, by Bartlett and Trachtenberg[11] in 1958, to be greatly stabilized by the π-acceptor action of a properly oriented α-carbonyl group in an equatorial position of the TBP transition state carbon. We therefore prepared **2a–c**, by the indicated route, and spectroscopically probed their structures.[12]

The green solutions of **2** in sealed tubes of liquid SO_2 (or SO_2-SO_2ClF) show no deterioration after weeks at room temperature. Quenching with aqueous NaOH cleanly produces anthracenes **5a–c**, presumably by two-electron reduction of **2a–c** with aqueous sulfite. The ^1H and ^{19}F NMR spectra[13] are best interpreted, by comparisons with many reference compounds, in terms of the symmetric structures **2a–c**. Among the alternative structures for **2** which were considered and ruled out were the sulfonium structures **6a–c** and **6′a–c** and the π-dication structures **7a–c**, primarily through comparisons with models **8a–c**,[14,15] **9**,[6b] and **10**.[6b]



5a-c

Evidence against structures **6** is adduced from the following. (a) The failure to see broadening in the single *p*-Me ^1H NMR peak of **2a** or, more convincingly, of the *p*-fluoro peak in the proton-decoupled ^{19}F NMR spectrum of **2c** at temperatures as low as −100 °C. The two ^{19}F substituents in **6c** would be expected to have a chemical shift difference of ~60 ppm, if one accepts **8c** (ϕ 52.8 ppm, SO_2) and **5c** (ϕ 114.6 ppm, $CDCl_3$) as appropriate models. The minimal broadening (~3 Hz) of the ^{19}F signal for **6c** on going from 30 to −100 °C therefore sets an upper limit of ~4 kcal/mol for $\Delta G^\ddagger_{-100\,°C}$ for the process interconverting **6c** and **6′c**. (b) The proton shown as R in **6a** or a rapidly equilibrating mixture of **6a** and **6′a** would

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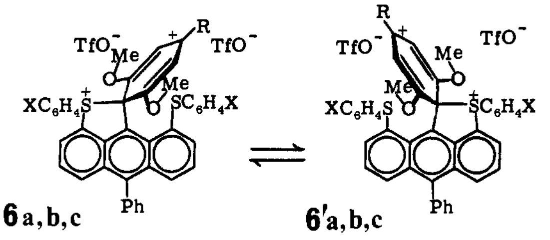
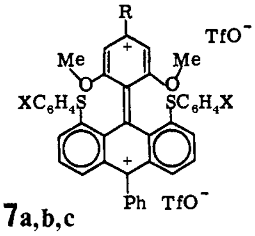
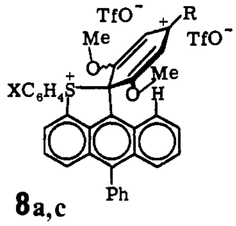


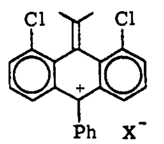
6a,b,c **6'a,b,c**



7a,b,c



8a,c



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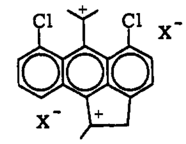

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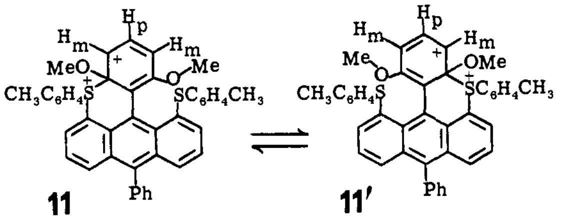
be expected to have a chemical shift comparable with that of the analogous proton in **8a** (δ 9.13, SO_2).[14] Its appearance at 0.70 ppm higher field (δ 8.43, SO_2) is best explained by nucleophilic involvement of the second sulfur as pictured for **2a.** (c) Nucleophilic involvement of the second sulfur as in **11** ⇌ **11'** is ruled out by the finding of the peak for H_p (δ 8.37) at much lower field than that for H_m (δ 6.47), a finding consistent with **2a** but not **11.**



11 **11'**

Structure **7a** (and also **11**) is ruled out by ^{1}H NMR comparisons with **9** and **10**, which are known[6b] to be π cations. The chemical shifts for the protons of the 10-phenyl substituents of monocation **3** (δ 7.55-7.41) and dication **2a** (δ 7.63-7.48) are comparable for these sulfonium ions, but are at considerably lower field for π-type monocation **9** (δ 7.82-7.45). The anthracene ring protons of π dication **10** (δ 9.32-8.44) are found at much lower field than those for dication **2a** (δ 8.22-7.72), as are those for several other π-cation analogues.[6b] This is in keeping with the postulated structure **2a,** in which one of the positive charges is localized in the pentadienyl system, producing the large downfield shift (δ 8.37) observed for the proton meta to the methoxyl substituents.

Although **2a** has been obtained in solid form, we have as yet been unable to grow crystals suitable for X-ray crystallography. Further work currently underway in our laboratory is designed to test our tentative conclusion that compounds **2a-c** do indeed have the structures here postulated for them, structures centered about pentavalent TBP carbon.

Acknowledgment. A grant (CA13963) from the National Cancer Institute supported this research and support during the writing of the paper was provided J.C.M. by the Alexander von Humboldt Foundation.

References and Notes

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(3) Olmstead, W. N.; Brauman, J. I. *J. Am. Chem. Soc.* **1977,** *99,* 4219, and references therein.

(4) See ref 9 of Brauman.[3] See also: (a) Gillespie, R. J. *J. Chem. Soc.* **1952,** 1002. (b) Firestone, R. A. *Tetrahedron* **1977,** *33,* 3009. (c) Schlegel, H. B.; Mislow, K.; Bernardi, F.; Bottoni, A. *Theoret. Chim. Acta* **1977,** *44,* 245. (d) Wolfe, S.; Kost, D. *J. Chem.* **1978,** *2,* 441.

(5) Much of the insight as to which structural features might be expected to stabilize species containing pentavalent TBP carbon comes from studies of species involving higher valence states of nonmetallic elements above the second row of the periodic table. (a) The stabilizing effect of a five-membered ring linking an apical and an equatorial position of a TBP molecule was, for example, recognized in Westheimer's laboratory in 1953 from studies of phosphate ester hydrolysis. (See Westheimer, F. H. *Acc. Chem. Res.* **1968,** *1,* 70.) (b) For recent studies of analogous compounds of I, S, P, and Si see: Perozzi, E. F.; Martin, J. C. *J. Am. Chem. Soc.* **1979,** *101,* 1591; *Science* **1976,** *191,* 154; and references cited therein.

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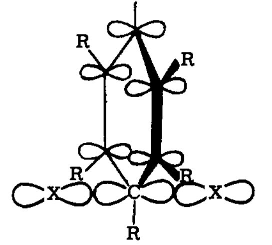
(7) (a) It should be noted that the pentavalent carbon species of this paper and of ref 6 differ from the pentacoordinate tetravalent carbon "onium" species, such as CH_5^+ and its analogues, which use eight electrons to bond five ligands to carbon, in that the five ligands to carbon in **1** or **2a-c** contribute ten electrons, formally expanding the carbon valence shell to 10: Field, F. H. *Acc. Chem. Res.* **1968,** *1,* 42. Olah, G. A.; Jouell, C. L.; White, A. M. *J. Am. Chem. Soc.* **1969,** *91,* 3961. Jemmis, E. D.; Chandrasekhan, J.; Schleyer, P. v. R. *ibid.* **1979,** *101,* 527. We say "formally" in recognition of the fact that the theoretical description of the bonding in such species, like that for analogous TBP compounds of pentacoordinate P, Si, or S,[5] places the "excess" electron density primarily on the apical ligands. The approximate bonding scheme called hypervalent by Musher[8] (very similar to that used by Pimentel[7b] to describe the hydrogen bond in bifluoride ion) describes the colinear apical bonds in terms which make this clear. We find the term "hypervalent" useful in describing such bonding despite objections recently raised to its use: Halgren, T. A.; Brown, L. D.; Kleier, D. A.; Lipscomb, W. N. *J. Am. Chem. Soc.* **1977,** *99,* 6793. For a response to these objections see: Harcourt, R. D. *ibid.* **1978,** *100,* 8060. (b) Pimentel, G. C. *J. Chem. Phys.* **1951,** *19,* 446.

(8) Musher, J. I. *Angew Chem., Int. Ed. Engl.* **1969,** *8,* 54.

(9) It is also possible that this six-membered ring may retain some of its aromatic character by using a pair of electrons in the hypervalent bond to complete the $[4n + 2]$ shell. We suggest that such aromaticity might be termed bis ipso aromaticity and propose its further study.



bis ipso aromatic ?

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(11) Bartlett, P. D.; Trachtenberg, E. N. *J. Am. Chem. Soc.* **1958,** *80,* 5808.

(12) All new compounds, except for the salts (which were not isolated in crystalline form), gave elemental analyses within 0.4% of the calculated values. Field desorption mass spectrometry gave molecular ions for the cations of those salts not characterized by elemental analysis. Electron impact (70 eV) mass spectrometry of anthracene **5a** showed a strong peak at *m/e* 314 for a dication of composition corresponding to **2a.**

(13) ^{1}H NMR spectra were obtained at 220 MHz and ^{19}F spectra at 56.2 MHz. ^{1}H NMR **2a** (SO_2, −51 °C): δ 8.43 (t, J = 8.6 Hz, 0.9, H meta to OCH_3), 8.22 (d, J = 8.7 Hz, 1.8, 2- and 7-anthryl C-H), 8.00 (d, J = 7.1 Hz, 1.9, 4- and 5-anthryl C-H), 7.72 (apparent t, unresolved d of d, 2.1, 3- and 6-anthryl C-H), 7.63-7.46 (m, 4.8, C_6H_5), 7.17 (d, J = 8.3 Hz, 4.1, H ortho to S), 6.82 (d, J = 8.0 Hz, 4.1, H meta to S), 6.52 (d, J = 8.6 Hz, 2.0, H ortho to OCH_3), 3.11 (s, 6.0, OCH_3), 2.22 (S, 6.0, C-CH_3). ^{19}F NMR for **2c** (SO_2-SO_2ClF, −100 °C, ϕ 97.0), for **8c** (SO_2-SO_2ClF, −100 °C, ϕ 52.8), and for **5c** ($CDCl_3$, 30 °C, ϕ 114.6) were multiplets, which coalesced to singlets upon irradiation of the ^{1}H region.

(14) Syntheses of **8a,c**[12] followed routes analogous to those used to prepare **2a-c,**

(15) ^{1}H NMR samples for **8a** were unstable above −20 °C (SO_2, −46 °C, 220 MHz): δ 9.13 (t, J = 8.6 Hz, 1.0, H meta to OCH_3), 8.33 (d, J = 8.6 Hz, 1.0, 2-anthryl C-H), 8.17 (d, J = 7.2 Hz, 1.0, 4-anthryl C-H), 8.10 (d, J = 8.9

Hz, 1.0, 5-anthryl C–H), 7.90 (apparent t, unresolved d of d, 1.0, 3-anthryl C–H), 7.77–7.48 (m, 10.7, C_6H_5, 6- and 7-anthryl C–H, H ortho to S), 7.42 (d, J = 8.4 Hz, 2.0, H meta to S), 7.11 (d, J = 8.1 Hz, 1.0, 8-anthryl C–H), 6.96 (d, J = 8.6 Hz, H ortho to $-OCH_3$), 3.77 (s, 6.0, OCH_3), 2.54 (s, 3.0, CCH_3).

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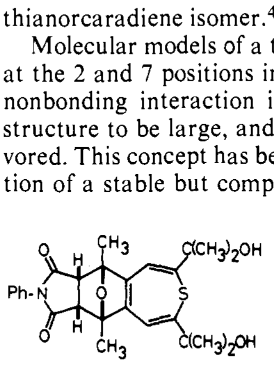
Synthesis of 2,7-Di-*tert*-butyl-4-ethoxycarbonyl-5-methylthiepin. A Remarkably Stable and Simple Monocyclic Thiepin[1]

Sir:

Heterocyclic 8-π electron systems, heteropins, have long been a subject of interest. In contrast to azepines and oxepins, which have been studied extensively,[2] little is known about thiepins because of their thermal instability owing to ready sulfur extrusion.[3] An accepted mechanism for this involves valence isomerization of the thiepin ring into its corresponding thianorcaradiene isomer.[4]

Molecular models of a thiepin possessing two bulky groups at the 2 and 7 positions indicate that these groups force the nonbonding interaction in corresponding thianorcaradiene structure to be large, and hence the thiepin form will be favored. This concept has been revealed by the successful isolation of a stable but complex thiepin (**1**),[5] whereas the compound having no bulky groups at these positions such as **2** never has been isolated though it can be generated and detected.[6]



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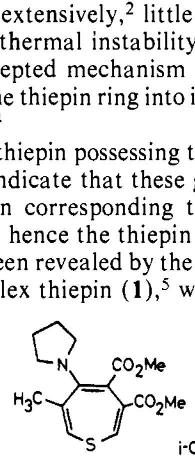

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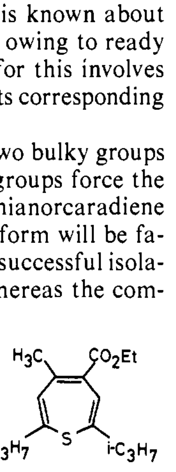

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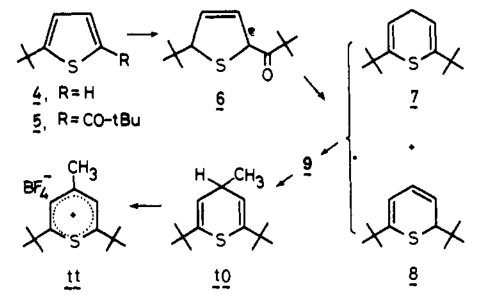
We have previously shown that the thiepin **3** undergoes ready sulfur extrusion ultimately to give the corresponding benzene derivative even at −70 °C.[7] We report here a first example of a simple thiepin stabilized by two bulky *tert*-butyl groups.[8]

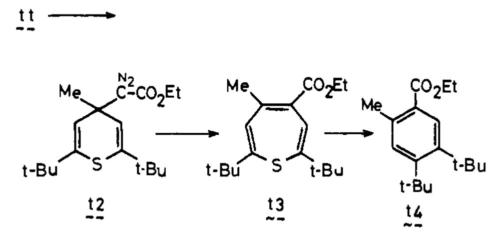
The synthesis of the key intermediate, 2,6-di-*tert*-butyl-4-methylthiopyrylium salt (**11**), is illustrated in Scheme I. The Friedel-Crafts reaction of 2-*tert*-butylthiophene (**4**)[9] with pivaloyl chloride ($SnCl_4$, in benzene at room temperature) gave crystalline 2-*tert*-butyl-5-pivaloylthiophene (**5**)[10] in 94% yield. Birch reduction of **5** (Li/NH_3, *t*-BuOH, −78 °C, 10 min) gave 88% 2-*tert*-butyl-5-pivaloyl-2,5-dihydrothiophene (**6**)[10] contaminated with small amounts (<5%) of the corresponding 2,3- and 4,5-dihydrothiophenes. Compound **6** was converted into **7** and **8** according to a novel strategy,[11] by treatment with a large excess of zinc dust and trimethylchlorosilane and quenching with 1 N sodium hydroxide. A 1:8 mixture of **7** and **8** was obtained in 86% yield[10] and was separated by column chromatography on silica gel with hexane. Hydride abstraction of the mixture of **7** and **8** ($Ph_3C^+BF_4^-/CH_3CN$) afforded the thiopyrylium salt (**9**)[10] in 68% yield. Methylation of **9** (CH_3Li in ether, −78 °C) gave the thiopyran **10**[10] which was finally converted into 2,6-di-*tert*-butyl-4-methylthiopyrylium tetrafluoroborate (**11**)[10] by the usual method. The 2,6-di-*tert*-butylthiopyrylium salt thus obtained was not readily accessible via previously available methodologies.[12]

The di-*tert*-butylthiopyrylium salt **11** was transformed into a thiepin ring system via the sequence of reactions shown in Scheme II. The thiopyrylium salt **11** was treated with ethyl lithiodiazoacetate[1,7,13] (in ether and THF, −120 °C) to give diazo compound **12**[10] (yellow needles, mp 32–33 °C, 90% yield). Treatment of **12** with π-allylpalladium chloride dimer (5 mol %, $CHCl_3$, 0 °C, 1 h) gave thiepin **13** (yellow prisms, mp 23.5–24.5 °C (from methanol), 99% yield). The structure of **13** ($C_{18}H_{28}O_2S$) was supported by elemental analysis for C, H, and S and spectroscopic data. The ^1H NMR spectrum shows signals of the *tert*-butyl groups at δ 1.22 and 1.23 (each s, 9 H), ring methyl protons doublet coupled with H-3 at 2.11 (d, J = 0.9 Hz), quartet of H-3 at 6.50 (J = 0.9 Hz), and singlet of H-6 at 6.14 along with the ethoxycarbonyl protons at 1.32 (t, 3 H, J = 7.1 Hz) and 4.23 (q, 2 H). ^{13}C NMR spectrum of **13** is also consistent with the structure.[14] Thiepin **13** exhibits UV maxima (in cyclohexane) at 234 nm (log ε 4.11) and 356 (2.95) with low-intensity tailing up to 510 nm.[15] The IR spectrum of **13** (KBr) shows typical absorption for an α,β-unsaturated ester carbonyl group at 1715 cm^{-1}.

Scheme I



Scheme II



In spite of its monocyclic thiepin structure, **13** shows remarkable thermal stability and can be handled under atmospheric conditions with no detectable decomposition. Its half-life at 131 °C in toluene-d_8 is 7.1 h.[16] On prolonged heating in toluene at 140 °C in a sealed tube **13** was converted in nearly quantitative yields into sulfur and ethyl 4,5-di-*tert*-butyl-2-methylbenzoate (**14**), colorless needles, mp 21–22 °C (from methanol). Anal. ($C_{18}H_{28}O_2$) C, H. The ^1H NMR of the compound **14** shows signals at δ 1.53 (s, 18 H), 2.43 (s, 3 H), 7.25 (s, 1 H), and 8.04 (s, 1 H), and the ethyl ester protons at 1.37 (t) and 4.27 (q, J = 7.0 Hz). The relatively downfield chemical shift of the *tert*-butyl groups is due to the ortho arrangement of the two *tert*-butyl groups in the benzene ring.[17] A comparison of **13** and **3** shows that substitution of *tert*-butyl groups for isopropyl groups on 2 and 7 positions of the thiepin ring produces high thermal stability.[18] Presumably, formation of the thianorcaradiene intermediate does not arise owing to increased steric hindrance.

The thiepin is isoelectronic with the cycloheptatrienide ion and, if planar, may actually be antiaromatic. Paratropicity[19] of thiepins associated with 8-π and 12-π electrons has been proposed for some complex thiepins.[5,20] In the NMR spectrum, the methyl proton of **13** is at δ 2.11, similar to that of the methyl group cis to methoxycarbonyl in methyl 3,3-dimethyl acrylate (δ 2.12).[21] Furthermore, the chemical shift of H-6 (δ 6.41) is in fair agreement with the value (δ 6.24) calculated by using the substituent shielding coefficient Z^{22} for olefinic protons. In addition, available X-ray crystallographic results of some thiepins[23] suggested that **13** must exist in a boat conformation. From these results we consider the thiepin **13** to be

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