

Branko S. Jursic* and Blaise LeBlanc

Department of Chemistry, University of New Orleans, New Orleans, Louisiana 70148

Received September 26, 1996

The transition state structures for the addition of maleic acid anhydride and methyl phenylpropiolate to 1-phenyl-3,4-dimethylphosphole were generated with the AM1 semiempirical method. The competitive transition state structures for 1,5-phenyl rearrangement in 1-phenyl-3,4-dimethylphosphole was also optimized with AM1. The energies were evaluated with the SVWN and Becke3LYP DFT methods using a 6-31G(d) basis set. The reaction outcome based on the evaluated energies were discussed and compared with experimental observations.

J. Heterocyclic Chem., **33**, 1389 (1996).

Introduction.

Chiral phosphorus compounds play a prominent role in asymmetric catalysis [1]. The major drawback of chiral phosphorus compounds, as metal complexation reagents that catalyzed many of the organic reactions, is that they have the potential to lose their optical activity. At least three distinct mechanisms can be used to explain the racemization of chiral phosphorus compounds. The simplest is phosphorus pyramidal inversion, with an estimated activation barrier of 30-35 kcal/mol [1]. If the reaction is carried out in a protic solvent, racemization of the chiral phosphorus can pro-

ceed through Berry pseudo rotation [2] of an intermediate phosphorane. The estimated activation barrier for this racemization is only 5 kcal/mol, which is allowable at room temperature. Edge-involved racemization, as proposed by Arduengo [3], occurs in this complex, as it involves a tetra coordinate phosphorus. From this racemization mechanism it is evident that chiral ligands, with phosphorus located at the bridgehead of small, rigid systems, cannot possibly undergo racemization through the mentioned above mechanisms. Norbornane derivatives with a bridgehead phosphorus could be an ideal chiral metal ligand.

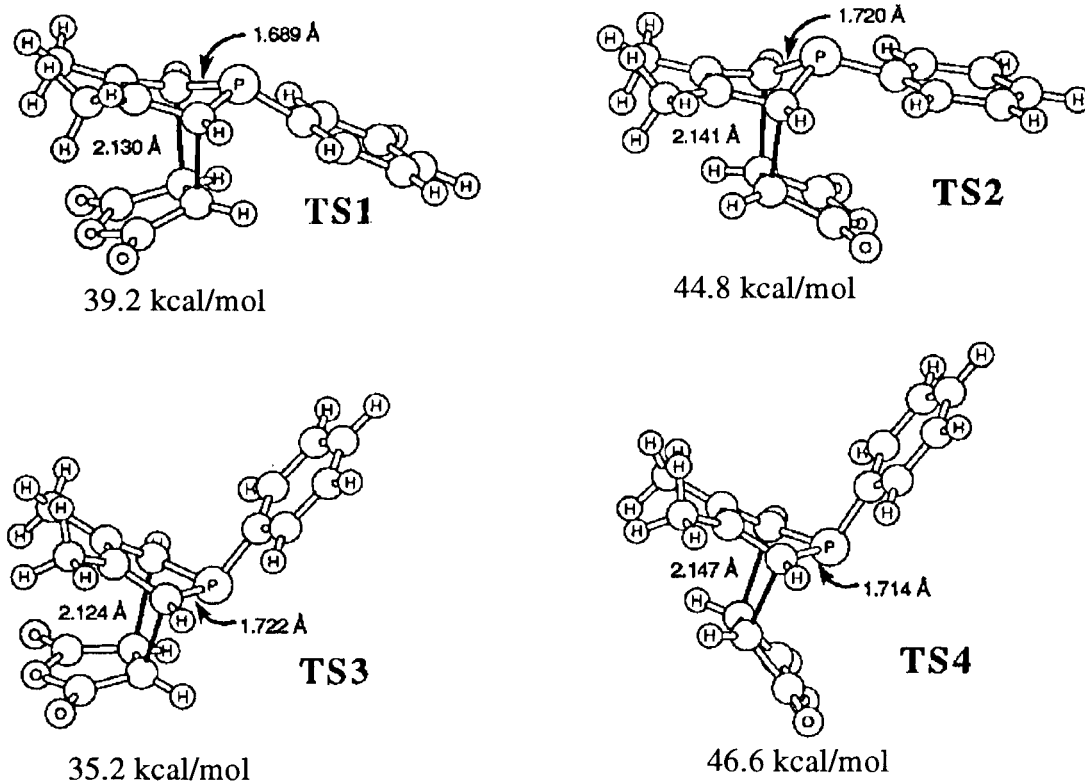


Figure 1. Four AM1 computed transition state structure of maleic anhydride addition to 1-phenyl-3,4-dimethylphosphole.

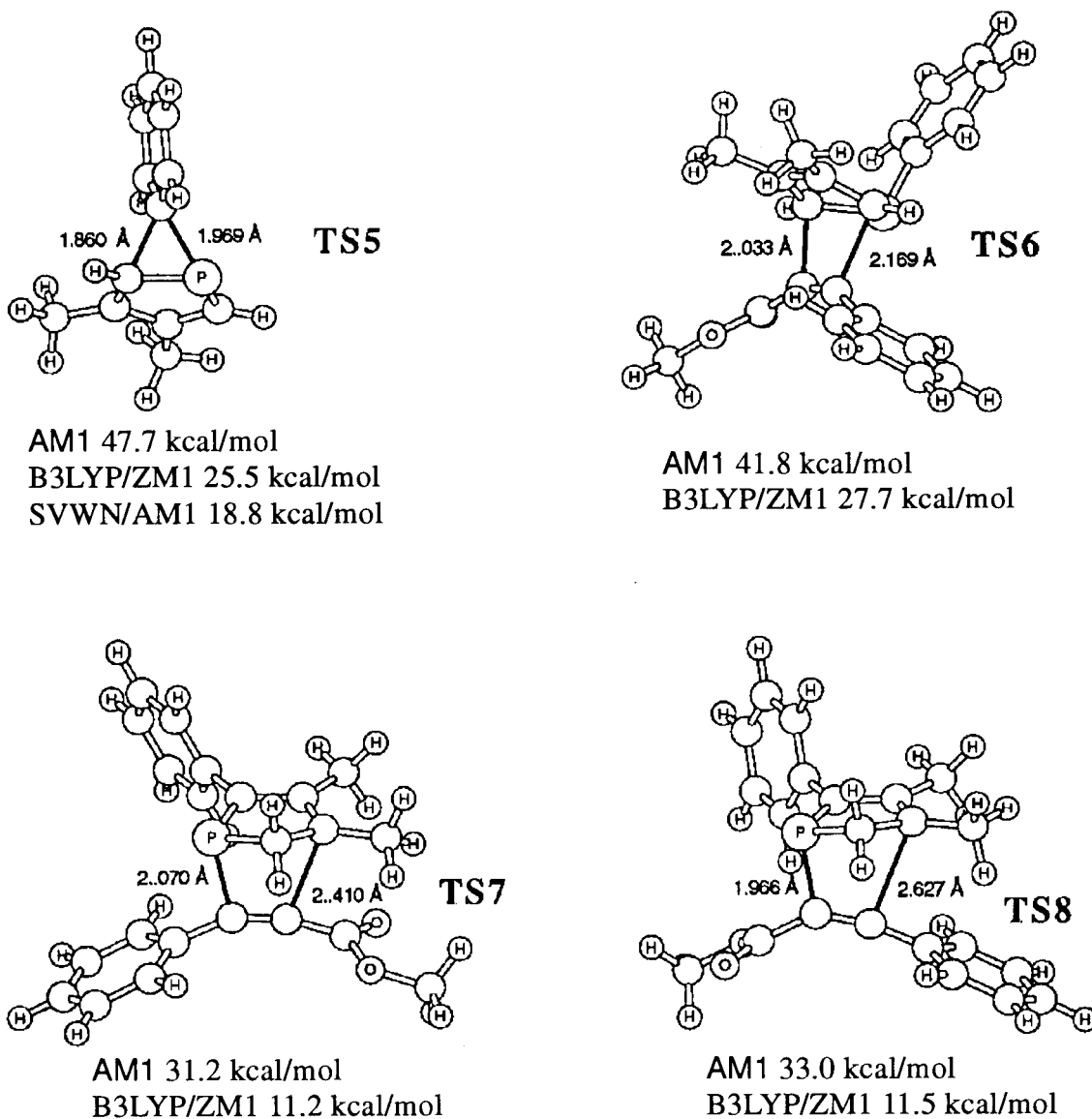


Figure 2. Transition state structures calculated by AM1 and energy estimated by DFT methods.

One promising synthetic procedure to prepare these bridgehead phosphorus compounds is through cycloaddition reactions between phosphorus five-membered heterocycles and the corresponding dienophiles. For example, substituted λ^3 phospholes react easily with maleic anhydride and *N*-phenylmaleimide to give the expected [4+2] Diels-Alder cycloadduct [4]. This discovery was rather surprising, considering λ^3 phospholes are aromatic heterocyclic compounds. Although heterocyclic compounds are synthones in some synthetic transformations [5], their use as dienes in the Diels-Alder reaction is limited [6]. The cycloaddition reaction with phosphorus containing heterocycles should be a major method of preparation for phosphorus chiral ligands

for organometallic catalyst. We present here our computational studies of the cycloaddition with λ^3 phospholes.

Methodology.

All semiempirical calculations were performed on a IBM RISC/6000 computer. Chem-3D Plus on a Macintosh IIx was used as a graphical interface for drawing and visualizing all structures and preparing input files for MOPAC [7]. The search for the transition states and their verification [8] was performed as described previously [9]. Vibrational and thermal analyses were performed on all optimized structures. All density functional theory (DFT) calculations were performed with the Gaussian 92 [10] implementation of DFT with the

6-31G(d) basis set [11]. Two DFT methods: Slater exchange functional [12] with Vosko, Wilk and Nusair correlation functional [13] (SVWN) and Beckes's 3 parameter functional [14] with Lee, Yang and Parr correlation functional [15] (B3LYP) were used to evaluate the energies.

Results and Discussion

To perform the study of the cycloaddition reaction, we selected 1-phenyl-3,4-dimethylphosphole among other λ^3 phospholes as a diene since experimental data for this system is available. Since this molecular system is rather large for a full DFT computational study, the AM1 [16] semiempirical method was chosen for geometric optimization. This method has proven to generate energies that are quite close to those obtained either experimentally or by high level ab initio calculations [16,17]. Although we have demonstrated that AM1 computed activation energies for Diels-Alder reactions with cyclobutadiene were not predicted correctly [18], it can be used for predicting the relative energies of similar reactions [19]. To support this approach we first investigated the addition of maleic anhydride to 1-phenyl-3,4-dimethylphosphole. The reaction was performed experimentally [4]. If we consider only concerted mechanisms for the cycloaddition reaction [20], four transition state structures are permitted (Figure 1). As we have demonstrated in many papers previously [20], we have excellent agreement between the computed reactivity and the products actually obtained [4]. It was determined that the products were obtained from the endo transition state structures of TS1 and TS3, with TS3 forming the major product. The AM1 computational results fully agree with the experimental results although the computed activation energy of 35.2 kcal/mol is rather high and would be difficult to achieve experimentally. The obtained AM1 computational study fails to predict activation energies accurately.

Recently we demonstrated that some DFT methods produce reliable activation energies for the Diels-Alder reaction [21]. For example the B3LYP/6-31G* computed activation energy of ethylene addition to butadiene is almost identical to the experimental value [21]. Although DFT studies are not as computational time demanding as electron correlated ab initio methods and can be applied to the moderately sized molecules [22], the chosen problem is still rather large to be computed with full DFT methodology. Thus we have implemented a DFT-AM1 computational approach for relatively large systems. It was demonstrated that computed DFT energies on AM1 geometries are almost identical to those obtained by full DFT computational studies. The B3LYP DFT method, in particular, gives accurate results [23]. We have modeled extrusion reactions with this method and obtained good correlation between experimental and the computed results [24].

Because two different types of reactions can be involved when 1-phenyl-3,4-dimethylphosphole is considered,

1,5-sigmatropic rearrangement and the Diels-Alder reaction, AM1 compute energies may not predict the correct pathway of the reaction (Figure 2). For example AM1 computed energies prefer cycloaddition (TS6) over the rearrangement (TS5) reaction by approximately 8 kcal/mol. Experimentally, there was not a trace of the product that should be formed through TS6 [2]. When the energy is evaluated by the Becke3LYP/6-31G(d) DFT method, rearrangement is preferred by nearly 2.2 kcal/mol suggesting a mixture of products may form through TS5 and TS6. Although we reported the extraordinary accuracy of this method for evaluating the activation energies of Diels-Alder reactions [21]; it considerably overestimates the activation energy for this particular sigmatropic rearrangement. We have demonstrated excellent agreement for rearrangement reactions, when SVWN DFT computed energies are considered [25]. The calculated energies favor rearrangement by 8.9 kcal/mol as a favorite process over cycloaddition. The rearranged reactant can then engage in cycloaddition with methyl phenylpropiolate. There are two possible isomeric transition state structures (TS7 and TS8). The AM1 computed energies suggest that this cycloaddition reaction has considerably lower energy if compared with a reaction through TS6. The Becke3LYP/6-31G* energy evaluation prefers this path even more.

Conclusion.

We reiterate our previous finding that AM1 energies are only reliable for relative comparisons of similar reactions; the DFT calculations provide more reliable results. Considering these calculations, if 1-phenyl-3,4-dimethylphosphole is reacted with a non reactive dienophile, 1,5-phenyl rearrangement is likely. The rearranged product is a more superior diene for the Diels-Alder reaction and will readily react with non reactive dienophiles. This conclusion was made on the basis of DFT energies, which are in full agreement with the experimental outcome of these reactions [2,4].

REFERENCES AND NOTES

- [1] For example see: H. B. Kagan, *Comprehensive Organometallic Chemistry*, G. Wilkinson, F. G. A. Stone and E. W. Abel, eds, Pergamon press, Oxford, **8**, 463 (1982).
- [2] A. Brèque, J.-M. Alcaraz, L. Ricard, F. Mathey, A. Tambuté and P. Macaudière, *New. J. Chem.*, **13**, 369 (1989) and references therein.
- [3] A. J. Arduengo III, *Pure Appl. Chem.*, **59**, 1053 (1987) and references therein.
- [4] F. Hughes and F. Mercier, *Tetrahedron Letters*, **22**, 319 (1981).
- [5] A. I. Meyers, *Heterocycles in Organic Synthesis*, E. C. Taylor and A. Weissberger, eds, John Wiley and Sons, New York, NY, 1974; B. H. Lipshutz, *Chem. Rev.*, **86**, 796 (1986); T. Masayoshi and Y. Gosei, *Kagaku Kyokaiishi*, **51**, 399 (1993); P. A. Jacobi, K. M. Touchette and H. G. Selnick, *J. Org. Chem.*, **57**, 6305 (1992).

- [6] D. L. Boger and S. N. Weinreb, *Hetero Diels-Alder Methodology in Organic Synthesis*, Academic Press, New York, NY, 1987; D. L. Boger, *Chem. Rev.*, **86**, 781 (1986); R. R. Schmidt, *Acc. Chem. Res.*, **19**, 250 (1986).
- [7] All calculations were carried out with MOPAC version 6.0. Quantum Chemistry Program Exchange (QCPE), Program Number 455, 1990.
- [8] The transition state must have only one imaginary frequency. For the transition state theory see: W. J. Albery, *Transition-State Theory Revision in Adv. Phys. Org. Chem.*, **28**, 139 (1993); R. A. Marcus, *Science*, **256**, 1523 (1992).
- [9] B. S. Jursic and Z. Zdravkovski, *J. Mol. Struct. (Theochem)*, **303**, 177 (1994) and references therein.
- [10] Gaussian 92/DFT, Revision G.2, M. J. Frisch, G. W. Trucks, H. B. Schlegel, P. M. W. Gill, B. G. Johnson, M. W. Wong, J. B. Foresman, M. A. Robb, M. Head-Gordon, E. S. Replogle, R. Gomperts, J. L. Andres, K. Raghavachari, J. S. Binkley, C. Gonzalez, R. L. Martin, D. J. Fox, D. J. Defrees, J. Baker, J. J. P. Stewart, and J. A. Pople, Gaussian, Inc., Pittsburgh PA, 1993.
- [11] For an explanation of GAUSSIAN basis sets see: M. J. Frisch, A. E. Frisch and J. B. Foresman, *Gaussian 94 User's Reference*, Gaussian, Inc. Pittsburgh, PA, 1994-1995.
- [12] J. C. Slater, *Quantum Theory of Molecular and Solids*, Vol 4, *The swlf-Consistent Field for Molecular and Solids*, McGraw-Hill, New York, 1974.
- [13] S. H. Vosko, L. Wilk and M. Nusair, *Can. J. Phys.*, **58**, 1200 (1980).
- [14] A. D. Becke, *J. Chem. Phys.*, **98**, 5648 (1993).
- [15] C. Lee, W. Yang, and R. G. Parr, *Phys. Rev. B*, **37**, 785 (1988).
- [16] M. J. S. Dewar, E. G. Zoebisch, E. F. Healy and J. J. P. Stewart, *J. Am. Chem. Soc.*, **107**, 3902 (1985); M. J. S. Dewar and E. G. Zoebisch, *J. Mol. Struct. (Theochem)*, **180**, 1 (1988).
- [17] K. N. Houk, Y.-T. Lin and J. D. Evansek, *Angew. Chem., Int. Ed. Engl.*, **31**, 682 (1992) and references therein.
- [18] B. S. Jursic and Z. Zdravkovski, *J. Mol. Struct. (Theochem)*, **309**, 249 (1994).
- [19] B. S. Jursic and Z. Zdravkovski, *J. Mol. Struct. (Theochem)*, **315**, 85 (1994); Branko S. Jursic and Z. Zdravkovski, *Bull. Chem. Technol. Macedonia*, **13**, 55 (1994); B. S. Jursic and Z. Zdravkovski, *J. Heterocyclic Chem.*, **31**, 1429 (1994); B. S. Jursic and D. Coupe, *J. Heterocyclic Chem.*, **32**, 483 (1995); B. S. Jursic, *J. Chem. Soc., Perkin Trans. 2*, 1217 (1995); B. S. Jursic, *J. Heterocyclic Chem.*, in press; B. S. Jursic, *J. Heterocyclic Chem.*, in press.
- [20] K. Houk, J. Gonzalez and Y. Li, *Acc. Chem. Res.*, **28**, 81 (1995) and references therein.
- [21] B. S. Jursic and Z. Zdravkovski, *J. Chem. Soc., Perkin Trans. 2*, 1223 (1995)
- [22] For application of DFT methods to chemical problems of interest see: J. M. Seminario and P. Politzer, eds, *Modern Density Functional Theory A Tool for Chemistry*, Elsevier, Amsterdam, 1995.
- [23] B. S. Jursic, *J. Mol. Struct. (Theochem)*, in press.
- [24] B. S. Jursic, *J. Chem. Soc., Perkin Trans 2*, in press.
- [25] B. S. Jursic, *J. Comp. Chem.*, in press; B. S. Jursic, manuscript in preparation.