JOC*Article*

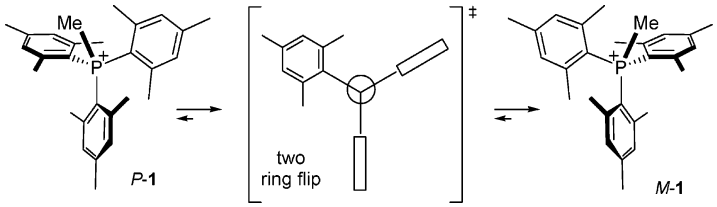
Trimesitylmethylphosphonium Cation. Supramolecular Stereocontrol and Simple Enantiomerization Mechanism Determination

Benoît Laleu,[†] Gérald Bernardinelli,[†] Remi Chauvin,[‡] and Jérôme Lacour*,[†]

Département de Chimie Organique, Université de Genève, quai Ernest-Ansermet 30, 1211 Genève 4, Switzerland, and Laboratoire de Chimie de Coordination, 205 route de Narbonne, 31077 Cedex 4, Toulouse, France

Jerome.Lacour@chiorg.unige.ch

Received May 29, 2006



Stereocontrol over the propeller isomerism of trimesitylmethylphosphonium cation was achieved through an ion pairing with chiral hexacoordinated phosphate anions; the asymmetric ion pairing allowed also a most simple experimental proof of the nature of the enantiomerization pathway in solution (two-ring flip).

Introduction

Triarylalkylphosphonium salts, and their triarylphosphane precursors, are known to adopt chiral three-bladed propeller geometries that differ, both in solution and in the solid-state, in the sense of twist of the three aromatic rings.[1] These moieties thus exist in two enantiomeric forms with *P* (clockwise) or *M* (counterclockwise) configurations (Figure 1).[2] As such, they belong to the class of compounds of type Ar_3ZX (Z = C, As, P, Si, etc.; X = H, R, lone pair, etc.), which has been particularly studied by Mislow and co-workers.[2]

Only few examples of configurationally stable three-bladed propellers have been reported in the literature.[3] Most systems, including triarylphosphanes and triarylphosphonium salts, present a rapid exchange between the enantiomers in solution prohibiting their isolation at room temperature in non racemic form.[4] In phosphane chemistry, even if the coordination of the P atom to organometallic moieties can modify the kinetics of $M \leftrightarrows P$ exchange, configurationally stable derivatives have never been isolated.[5] Partial or full control of the propeller configuration is however feasible if the phosphorus atom is bound to a stereogenic organometallic center.[6] For simple triarylalkylphosphonium derivatives, such an asymmetric induction is obviously not feasible. Herein, we report the first example of a supramolecular stereocontrol over the propeller geometry of a phosphonium cation and, maybe more importantly, the first experimental evidence of the solution enantiomerization mechanism using a simple kinetic analysis and two readily determined rate constants.

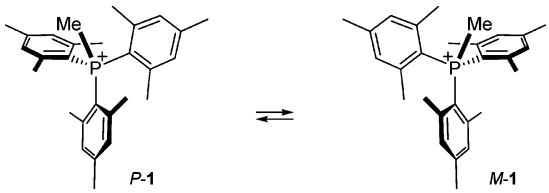


FIGURE 1. Interconverting helical configurations (*P* and *M*) of trimesitylmethylphosphonium cation **1**.

[†] Université de Genève.

[‡] Laboratoire de Chimie de Coordination.

(1) Allen, D. W. *Organophosphorus Chem.* **2005**, *34*, 1−76. Strohbusch, F. *Tetrahedron* **1972**, *28*, 1915−1926. Daly, J. J. *J. Chem. Soc.* **1964**, 3799−3810.

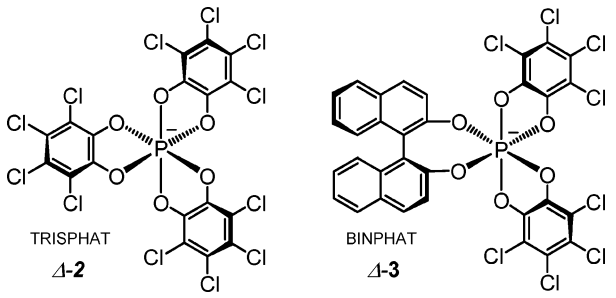
(2) Mislow, K. *Acc. Chem. Res.* **1976**, *9*, 26−33. Mislow, K.; Gust, D.; Finocchiaro, P.; Boettcher, R. J. *Top. Curr. Chem.* **1974**, *47*, 1−28. Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1973**, *95*, 1535−1547 and references therein.

(3) To our knowledge, only perchlorotriphenylamine, ethano-bridged triarylboranes, and bis- and tris(benzimidazol-1-yl)methane derivatives have been isolated in optically pure form: Bobosik, V.; Lopez, C.; Claramunt, R. M.; Roussel, C.; Stein, J. L.; Thiery, D.; Elguero, J. *Heterocycles* **1993**, *35*, 1067−1074. Okada, K.; Inokawa, H.; Oda, M. *Tetrahedron Lett.* **1991**, *32*, 6363−6366. Foces-Foces, C.; Hernandez Cano, F.; Martinez-Ripoll, M.; Faure, R.; Roussel, C.; Claramunt, R. M.; Lopez, C.; Sanz, D.; Elguero, J. *Tetrahedron: Asymmetry* **1990**, *1*, 65−86. Okamoto, Y.; Yashima, E.; Hatada, K.; Mislow, K. *J. Org. Chem.* **1984**, *49*, 557−558. Hayes, K. S.; Nagumo, M.; Blount, J. F.; Mislow, K. *J. Am. Chem. Soc.* **1980**, *102*, 2773−2776.

10.1021/jo061097w CCC: $33.50
Published on Web 08/17/2006

Results and Discussion

As just mentioned, the $M \leftrightarrows P$ exchange between the enantiomers of triarylalkylphosphonium cations is rapid in solution.[4] Only phosphorus compounds bearing hindered aryl groups exhibit slow rotation phenomena of the aromatic substituents on the NMR time scale (milliseconds).[7,8] For instance, at 20 °C, trimesitylmethylphosphonium cation **1** displays distinct signals for the chemically nonequivalent ortho and ortho′ methyl substituents, as well as meta and meta′ hydrogen atoms; these atoms (groups) being diastereotopic owing to their different geometrical environment.[2] Nevertheless, enantiomerization kinetics remains fast for **1** in solution (in the order of seconds).[7] Phosphonium cation **1** was never reported in nonracemic form.



Previously, hexacoordinated phosphorus anions TRISPHAT **2** [9] and BINPHAT **3** [10] have been shown to be general NMR chiral solvating,[11] resolving, and asymmetry-inducing reagents for chiral cationic species.[12] When associated with configurationally labile cations, supramolecular diastereoselective interactions occur and one diastereomeric ion pair can become predominant in solution (Pfeiffer effect).[13] An association of configurationally labile **1** with anions **2** and **3** was thus considered for the stereocontrol of the phosphonium cation. Salts [**1**][Δ-**2**] and [**1**][Δ-**3**] were prepared,[14] and the chiral recognition (induction) was studied by ^{1}H and ^{31}P NMR spectroscopy (toluene-d_8, 5.0×10^{-3} M).

In accordance with our expectations, an enantio-differentiation was observed ($\Delta\delta_{max} \approx 0.60$ ppm, P^+CH_3, salt (−)-[**1**][Δ-**2**]) and a decent diastereomeric excess was measured by the integration of the separated signals (de 39 and 47% for salts of anions **2** and **3**, respectively, see Supporting Information). Upon increasing solvent polarity, a decrease in diastereoselectivity can be observed as a result of looser electrostatic interactions and solvent competition ($CDCl_3$: de 20 and 26%; CD_2Cl_2: de 0%). X-ray quality crystals of salt (−)-[**1**][Δ-**2**] were obtained, and low-temperature structural analysis revealed a complete interionic induction and a preferred "heterochiral" association.[15] Two ion pairs are present in the asymmetric unit with virtually identical structures. Cations and anions adopt three-bladed propeller geometries of opposite helical configurations, *M* and Δ respectively (Figure 2).[16] Their C_3-axes are almost aligned (P^+−Me···P− bond angles 162.2(8) and 172.4(7)°); the apical methyl group of the phosphonium cations are in close contact with the oxygen atoms of the neighboring phosphate anions.[17] To our knowledge, it is the first example of a supramolecular stereocontrol over the configuration of this important type of three-bladed propeller moieties. In addition, and maybe more interestingly, the NMR differentiation of the *M* and *P* enantiomers of **1** allows the simple determination of the enantiomerization mechanism of the cation.

Enantiomerization of compounds of type Ar_3Z and Ar_3ZX is known to occur by "correlated" rotations of the aromatic rings. This is commonly analyzed in terms of Kurland's "flip" mechanism.[18] Four enantiomerization pathways are possible:

(4) Fang, X.; Scott, B. L.; John, K. D.; Kubas, G. J.; Watkin, J. G. *New J. Chem.* **2000**, *24*, 831−833. Howell, J. A. S.; Fey, N.; Lovatt, J. D.; Yates, P. C.; McArdle, P.; Cunningham, D.; Sadeh, E.; Gottlieb, H. E.; Goldschmidt, Z.; Hursthouse, M. B.; Light, M. E. *J. Chem. Soc., Dalton Trans.* **1999**, 3015−3028. Whitnall, M. R.; Hii, K. K.; Thornton-Pett, M.; Kee, T. P. *J. Organomet. Chem.* **1997**, *529*, 35−50. Palau, C.; Berchadsky, Y.; Chalier, F.; Finet, J.-P.; Gronchi, G.; Tordo, P. *J. Phys. Chem.* **1995**, *99*, 158−163. Howell, J. A. S.; Palin, M. G.; Yates, P. C.; McArdle, P.; Cunningham, D.; Goldschmidt, Z.; Gottlieb, H. E.; Hezroni-Langerman, D. *J. Chem. Soc., Perkin Trans. 2* **1992**, 1769−1775. Brown, J. M.; Mertis, K. *J. Organomet. Chem.* **1973**, *47*, C5−C7. Whitesides, G. M.; Bunting, W. M. *J. Am. Chem. Soc.* **1967**, *89*, 6801−6802.

(5) Baber, R. A.; Orpen, A. G.; Pringle, P. G.; Wilkinson, M. J.; Wingad, R. L. *J. Chem. Soc., Dalton Trans.* **2005**, 659−667. Niyomura, O.; Iwasawa, T.; Sawada, N.; Tokunaga, M.; Obora, Y.; Tsuji, Y. *Organometallics* **2005**, *24*, 3468−3475. Romeo, R.; Plutino, M. R.; Romeo, A. *Helv. Chim. Acta* **2005**, *88*, 507−522. Faller, J. W.; Parr, J.; Lavoie, A. R. *New J. Chem.* **2003**, *27*, 899−901. Bott, R. C.; Bowmaker, G. A.; Buckley, R. W.; Healy, P. C.; Perera, M. C. S. *Austr. J. Chem.* **2000**, *53*, 175−181. Alyea, E. C.; Ferguson, G.; Kannan, S. *Polyhedron* **2000**, *19*, 2211−2213. Howell, J. A. S.; Lovatt, J. D.; McArdle, P.; Cunningham, D.; Maimone, E.; Gottlieb, H. E.; Goldschmidt, Z. *Inorg. Chem. Commun.* **1998**, *1*, 118−120. Bayler, A.; Schier, A.; Bowmaker, G. A.; Schmidbaur, H. *J. Am. Chem. Soc.* **1996**, *118*, 7006−7007. Burckhardt, U.; Gramlich, V.; Hofmann, P.; Nesper, R.; Pregosin, P. S.; Salzmann, R.; Togni, A. *Organometallics* **1996**, *15*, 3496−3503. Fornies, J.; Martin, A.; Navarro, R.; Sicilia, V.; Villarroya, P. *Organometallics* **1996**, *15*, 1826−1833. Garner, S. E.; Orpen, A. G. *J. Chem. Soc., Dalton Trans.* **1993**, 533−541. Polowin, J. E.; Mackie, S. C.; Baird, M. C. *Organometallics* **1992**, *11*, 3724−3730. Davies, S. G.; Derome, A. E.; McNally, J. P. *J. Am. Chem. Soc.* **1991**, *113*, 2854−2861. Chudek, J. A.; Hunter, G.; MacKay, R. L.; Kremminger, P.; Schloegl, K.; Weissensteiner, W. *J. Chem. Soc., Dalton Trans.* **1990**, 2001−2005.

(6) Brunner, H.; Oeschey, R.; Nuber, B. *Organometallics* **1996**, *15*, 3616−3624. Brunner, H.; Oeschey, R.; Nuber, B. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 866−869.

(7) Bellamy, A. J.; Gould, R. O.; Walkinshaw, M. D. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1099−1104.

(8) Sutoh, K.; Sasaki, S.; Yoshifuji, M. *Inorg. Chem.* **2006**, *45*, 992−998. Boere, R. T.; Zhang, Y. *J. Organomet. Chem.* **2005**, *690*, 2651−2657. Ohzu, Y.; Goto, K.; Kawashima, T. *Angew. Chem., Int. Ed.* **2003**, *42*, 5714−5717. Yamaguchi, S.; Akiyama, S.; Tamao, K. *J. Organomet. Chem.* **2002**, *646*, 277−281. Matsumoto, T.; Kasai, T.; Tatsumi, K. *Chem. Lett.* **2002**, 346−347. Alyea, E. C.; Malito, J. *Phosphorus, Sulfur Silicon Relat. Elem.* **1989**, *46*, 175−181. Blount, J. F.; Maryanoff, C. A.; Mislow, K. *Tetrahedron Lett.* **1975**, 913−916. Stepanov, B. I.; Bokanov, A. I.; Svergun, V. I. *Zh. Obshch. Khim.* **1971**, *41*, 533−536. Rieker, A.; Kessler, H. *Tetrahedron Lett.* **1969**, 1227−1230 and references therein.

(9) Tris(tetrachlorobenzenediolato)phosphate(V): Favarger, F.; Goujon-Ginglinger, C.; Monchaud, D.; Lacour, J. *J. Org. Chem.* **2004**, *69*, 8521−8524. Lacour, J.; Ginglinger, C.; Grivet, C.; Bernardinelli, G. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 608−610.

(10) Bis(tetrachlorobenzenediolato)mono([1, 1′]binaphthalenyl-2, 2′-diolato) phosphate(V) anion: Lacour, J.; Londez, A.; Goujon-Ginglinger, C.; Buss, V.; Bernardinelli, G. *Org. Lett.* **2000**, *2*, 4185−4188.

(11) Previous results have shown that **2** and **3** are effective NMR chiral solvating agents for diaryldialkyl and triarylalkylphosphonium salts bearing stereogenic phosphorus and carbon atoms: Hebbe, V.; Londez, A.; Goujon-Ginglinger, C.; Meyer, F.; Uziel, J.; Jugé, S.; Lacour, J. *Tetrahedron Lett.* **2003**, *44*, 2467−2471. Ginglinger, C.; Jeannerat, D.; Lacour, J.; Jugé, S.; Uziel, J. *Tetrahedron Lett.* **1998**, *39*, 7495−7498.

(12) Lacour, J.; Frantz, R. *Org. Biomol. Chem.* **2005**, *3*, 15−19. Lacour, J.; Hebbe-Viton, V. *Chem. Soc. Rev.* **2003**, *32*, 373−382.

(13) Yeh, R. M.; Raymond, K. N. *Inorg. Chem.* **2006**, *45*, 1130−1139. Bergman, S. D.; Frantz, R.; Gut, D.; Kol, M.; Lacour, J. *Chem. Commun.* **2006**, 850−852. Vignon, S. A.; Wong, J.; Tseng, H. R.; Stoddart, J. F. *Org. Lett.* **2004**, *6*, 1095−1098. Hiraoka, S.; Harano, K.; Tanaka, T.; Shiro, M.; Shionoya, M. *Angew. Chem., Int. Ed.* **2003**, *42*, 5182−5185. Green, M. M.; Khatri, C.; Peterson, N. C. *J. Am. Chem. Soc.* **1993**, *115*, 4941−4942. Owen, D. J.; VanDerveer, D.; Schuster, G. B. *J. Am. Chem. Soc.* **1998**, *120*, 1705−1717. Kirschner, S.; Ahmad, N.; Munir, C.; Pollock, R. J. *Pure Appl. Chem.* **1979**, *51*, 913−923. Norden, B.; Tjerneld, F. *FEBS Lett.* **1976**, *67*, 368−370. Pfeiffer, P.; Quehl, K. *Ber. Dtsch. Chem. Ges.* **1931**, *64B*, 2667−2671.

(14) Lacour, J.; Barchéchath, S.; Jodry, J. J.; Ginglinger, C. *Tetrahedron Lett.* **1998**, *39*, 567−570.

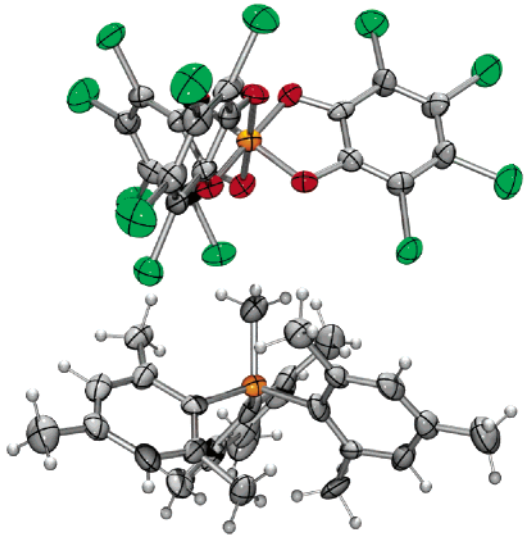
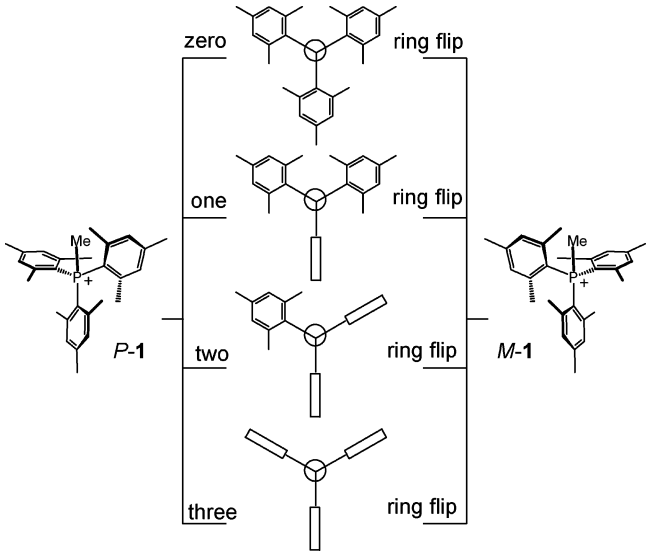


FIGURE 2. X-ray crystal structure of [*M*-**1**][Δ-**2**]. Ellipsoids are represented with 50% probability level.

zero-, one-, two-, or three-ring flip. A "*n*-ring flip" is defined by the rotation of *n* ring(s) in the same direction through a conformation in which the plane of the ring(s) is (are) perpendicular to a reference plane (defined by the three aryl carbon atoms attached to the central atom) while the other ring(s) (3-*n*) rotate(s) in the opposite direction through the reference plane (Scheme 1).

Force field calculations and structure-correlation studies advocate for the two ring-flip as the general rotational mechanism for propeller stereoisomerization.[19,20] This is also substantiated by most dynamic NMR experiments with elaborated Ar_3Z and Ar_3ZX substrates.[21] In a few cases, no clear-cut

SCHEME 1. The Four Possible Flip Processes for the Enantiomerization of Cation 1[a]



[a] Structures in the middle represent the four transition states viewed along the P^+-CH_3 bond.

mechanism could be established, and a one-ring flip pathway has been determined for azulene analogues of triphenylmethyl cations.[22,23] Recently, in the case of tris(pentafluorophenyl)-borane-benzotriazole adducts, a complex three-step process involving all the perfluorinated rings was determined for the enantiomerization process.[24]

As there is always the possibility that substituents introduced on the Ar_3Z and Ar_3ZX substrates to create a "residual isomerism" may modify the mechanism profile, an alternative method for the discrimination of the four possible interconversion pathways was sought; this method being possibly simpler than the deconvolution of matrixes of 4 to 32 conformations.[25]

In fact, the simplest method for a C_3-symmetrical molecule would be a direct comparison of the global rate of enantiomerization ($k_{enantio}$, $M \leftrightarrows P$ interconversion) with the rate of NMR exchange of diastereotopic groups on the aromatic residues ($k_{exchange}$, e.g., $Me_{ortho} \leftrightarrows Me_{ortho'}$). Bellamy and co-workers have

(15) Crystal data for [*M*-**1**][Δ-**2**]: $[(C_{28}H_{36}P)^+ (C_{18}Cl_{12}O_6P)^-]_2 (C_6H_{12}) (C_4H_8O_2)_{1.5}$; $M_r = 2562.7$; $\mu = 0.63$ mm^{-1}, $\rho_{calcd} = 1.362$ g·cm^{-3}, monoclinic, $P2_1$, $Z = 2$ ($Z' = 2$), $a = 12.3799(5)$, $b = 24.2382(12)$, $c = 21.2644(10)$ Å, $V = 6248.0(5)$ Å^3. Cell dimensions and intensities were measured at 200 K on a diffractometer with graphite-monochromated Mo Kα radiation ($\lambda = 0.71073$ Å). Of 49644 measured reflections, 24214 were unique and 9272 were observed ($|Fo| > 4\sigma(Fo)$). Data were corrected for Lorentz and polarization effects and for absorption: $R = 0.044$, $\omega R = 0.042$, $S = 1.28(2)$, Flack parameter $x = 0.06(10)$. Both ion pairs of the asymmetric unit are similar. CCDC-297893 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, U.K. Fax: (+ 44) 1223−336−033 or deposit@ccdc.cam.ac.uk).

(16) No evidence has so far been found to demonstrate the predominance of this relative configuration in solution. Configuration assignment of **1** by circular dichroism analysis of salts [**1**][Δ-**2**] and [**1**][Δ-**3**] could not be readily achieved because of the presence of the CD-active anions and of the aromatic solvent.

(17) In the predominant diastereomeric ion pair of (−)-[**1**][Δ-**2**], the ^{1}H NMR signal of P^+CH_3 is shifted towards higher frequencies (comparison with [**1**][I$^-$]), this being possibly the result of charge-assisted C−H···O interactions. On the contrary, a high field shift is observed for the minor diastereomer.

(18) Kurland, R. J.; Schuster, I. I.; Colter, A. K. *J. Am. Chem. Soc.* **1965**, *87*, 2279−2281. Colter, A. K.; Schuster, I. I.; Kurland, R. J. *J. Am. Chem. Soc.* **1965**, *87*, 2278−2279.

(19) Hummel, J. P.; Zurbach, E. P.; DiCarlo, E. N.; Mislow, K. *J. Am. Chem. Soc.* **1976**, *98*, 7480−7483. Kates, M. R.; Andose, J. D.; Finocchiaro, P.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1975**, *97*, 1772−1778. Andose, J. D.; Mislow, K. *J. Am. Chem. Soc.* **1974**, *96*, 2168−2176.

(20) Bürgi, H. B.; Dunitz, J. D. *Acc. Chem. Res.* **1983**, *16*, 153−161. Bye, E.; Schweizer, W. B.; Dunitz, J. D. *J. Am. Chem. Soc.* **1982**, *104*, 5893−5898. Brock, C. P.; Ibers, J. A. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1973**, *29*, 2426−2433.

(21) Khuong, T.-A. V.; Zepeda, G.; Sanrame, C. N.; Dang, H.; Bartberger, M. D.; Houk, K. N.; Garcia-Garibay, M. A. *J. Am. Chem. Soc.* **2004**, *126*, 14778−14786. Sedó, J.; Ventosa, N.; Molins, M. A.; Pons, M.; Rovira, C.; Veciana, J. *J. Org. Chem.* **2001**, *66*, 1579−1589. Toyota, S.; Asakura, M.; Oki, M.; Toda, F. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 2357−2362. Strekowski, L.; Lee, H.; Lin, S.-Y.; Czarny, A.; Van Derveer, D. *J. Organomet. Chem.* **2000**, *65*, 7703−7706. Lambert, J. B.; Stern, C. L.; Zhao, Y.; Tse, W. C.; Shawl, C. E.; Lentz, K. T.; Kania, L. *J. Organomet. Chem.* **1998**, *568*, 21−31. Rappoport, Z.; Biali, S. E. *Acc. Chem. Res.* **1997**, *30*, 307−314. Lockhart, J. C.; McDonnell, M. B.; Clegg, W.; Hill, M. N. S. *J. Chem. Soc., Perkin Trans. 2* **1987**, 639−649. Wille, E. E.; Stephenson, D. S.; Capriel, P.; Binsch, G. *J. Am. Chem. Soc.* **1982**, *104*, 405−415. Finocchiaro, P.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1974**, *96*, 2176−2182. Finocchiaro, P.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1974**, *96*, 3205−3213. Blount, J. F.; Finocchiaro, P.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1973**, *95*, 7019−7029. Rakshys, J. W., Jr.; McKinley, S. V.; Freedman, H. H. *J. Am. Chem. Soc.* **1971**, *93*, 6522−6529. Rakshys, J. W., Jr.; McKinley, S. V.; Freedman, H. H. *J. Am. Chem. Soc.* **1970**, *92*, 3518−3520.

(22) Clegg, W.; Lockhart, J. C. *J. Chem. Soc., Perkin Trans. 2* **1987**, 1621−1627.

(23) Ito, S.; Morita, N.; Asao, T. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 1409−1436. Ito, S.; Morita, N.; Asao, T. *Tetrahedron Lett.* **1992**, *33*, 6669−6672.

(24) Focante, F.; Leardini, R.; Mazzanti, A.; Mercandelli, P.; Nanni, D. *Organometallics* **2006**, *25*, 2166−2172 and references therein.

(25) Finocchiaro, P.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1974**, *96*, 3198−3205.

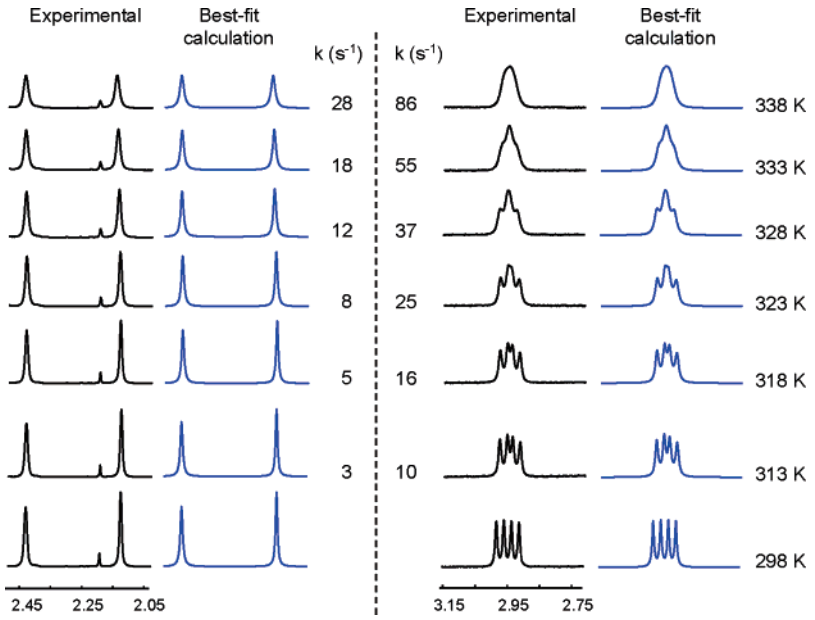


FIGURE 3. Salt [**1**][Δ-**2**] (^{1}H NMR, parts, 17% DMSO-d_6 in toluene-d_8, 500 MHz): left column, experimental and best-fit calculated spectra (*o*-CH_3 region, δ 2.45−2.00 ppm); right column, experimental and best-fit calculated spectra (CH_3P$^+$ region, δ 3.15−2.70 ppm).

indicated that the four threshold "*n*-ring flip" pathways lead to different mathematical relationships between $k_{enantio}$ and $k_{exchange}$. The ratio $k_{enantio}/k_{exchange}$ is equal to 3:3 for the zero-ring flip, 3:2 for the one-ring flip, 3:1 for the two-ring flip, and is undefined for the three-ring flip.[26,27] Independent measurements of $k_{enantio}$ and $k_{exchange}$ thus afford a simple method of determination of the mechanism pathway. While the determination of $k_{exchange}$ has never been an issue in this chemistry, the direct measurement of $k_{enantio}$ has been elusive. Studies have been performed in achiral medium, and the lack of differentiation of the *M* and *P* enantiomers of Ar_3Z or Ar_3ZX substrates have forbidden the measurement of the global rate of enantiomerization. In view of the NMR spectra obtained in the presence of anions **2** and **3**, we reasoned that salts [**1**][Δ-**2**] and [**1**][Δ-**3**] were giving a unique opportunity to determine simply and rapidly the rate of diastereomerization of **1**, which, under certain conditions,[28] can be virtually regarded as the rate of enantiomerization, $k_{enantio}$.

^{1}H NMR analysis of phosphonium iodide salt [**1**][I$^-$] at 298 K confirmed, in various solvent conditions, the slow rotation of the aromatic substituents on the NMR time scale. Rather large differences were observed for the diastereotopic meta hydrogen atoms and ortho methyl groups (e.g., $\Delta\delta$ 0.32 and 0.54 ppm, respectively, toluene-d_8 (3% DMSO-d_6)). Variable temperature (VT) NMR experiments were performed in DMSO-d_6 and in toluene-d_8 (3% DMSO-d_6). A dynamic conformational isomerism was detected at elevated temperatures (Supporting Information). Experimental values for $k_{exchange}$ were determined by line-shape analysis (WinDNMR) of the broadened exchange signals. Interestingly, no difference can be noted for the experiments performed in polar and apolar media (Supporting Information) and, more importantly for the kinetic mechanistic analysis, even in the presence of a chiral counterion (vide infra, and Figure 3, left column).

For the experimental determination of $k_{enantio}$ (and the confirmation of the value of $k_{exchange}$), salt [**1**][Δ-**2**] was selected.[29] Care was taken to optimize solvent conditions (17% DMSO-d_6 in toluene-d_8) that minimize the influence of the chiral counterion and present a complete lack of diastereoselective interactions (de 0%),[26] the conditions allowing still a large enough differentiation of the signals of the *M* and *P* enantiomers for the determination of $k_{enantio}$ (e.g., CH_3P$^+$, Figure 3, right column and Supporting Information) and a lack of differentiation of the diastereotopic atoms or groups to determine (again) $k_{exchange}$ (e.g., $Me_{ortho}/Me_{ortho'}$).

A dynamic isomerism was detected at elevated temperatures as the doublet signals of CH_3P$^+$ and the singlets of the $Me_{ortho}/Me_{ortho'}$ broadened upon temperature increase. Line-shape analysis afforded, for each spectrum, values for both $k_{enantio}$ and $k_{exchange}$.[30] Comparison of the experimental values of $k_{exchange}$ and $k_{enantio}$ at various temperatures (313−338 K) indicates clearly the existence of a 1:3 ratio between the values; this direct observation constitutes the proof of a two-ring flip mechanism for the trimesitylmethylphosphonium cation **1**, which was so far only an assumption in solution for this particular propeller.[7]

(26) $k_{enantio}$, the rate of enantiomerization, takes into account the motion of all three of the aromatic groups. However, $k_{exchange}$, the rate of NMR exchange of diastereotopic groups or atoms only includes the contribution of rings rotating in the direction opposite to a "flip". As a matter of fact, when rings rotate in that direction, diastereotopic atoms or groups exchange their relative positions and the dynamics of the process appear in VT-NMR. However, when an individual aromatic ring "flip", diastereotopic atoms or groups assume enantiotopic positions after rotation. As such, "flip" motions cannot be detected in NMR spectroscopy and do not contribute to $k_{exchange}$.

(27) In the case of the three-ring flip mechanism, all three "flip" motions cannot be detected in NMR spectroscopy. The rate of $k_{exchange}$ cannot be determined experimentally. The ratio $k_{enantio}/k_{exchange}$ is thus undefined.

(28) As shown previously, apolar solvent conditions favor a chiral recognition among the three-bladed propellers leading to the predominance of one diastereomeric salt over the other. In such conditions, the rate of isomerization from the major diastereoisomer to the minor isomer is different (slower) from the reverse isomerization rate. Care was thus taken to select "polar" conditions under which the diastereomeric ratio is 1:1 and the rate of diastereomerization of the salt can be virtually regarded as the rate of enantiomerization, $k_{enantio}$.

(29) TRISPHAT **2** is the better NMR chiral solvating agent and, at the same time, the less effective asymmetry-inducing moiety. As such, it is more effective for the kinetic mechanistic analysis.

(30) Care was taken to perform the line-shape analysis affording values for $k_{enantio}$ and $k_{exchange}$ on the very same proton spectra as to minimize the temperature error which would have been, otherwise, not negligible.

TABLE 1. Activation Parameters ($\Delta H^{\ddagger}$, $\Delta S^{\ddagger}$, and $\Delta G^{\ddagger}$) for the Diastereotopic Groups (Atoms) Exchange and Global Enantiomerization Barriers (T = 298 K)

salts of **1**	signals	$\Delta H^{\ddagger a}$	$\Delta S^{\ddagger b}$	$\Delta G^{\ddagger a}$
[**1**][I$^-$]^c	*m*-H	17.6 ± 0.2	−0.2 ± 0.01	17.7 ± 0.2
[**1**][I$^-$]^c	*o*-CH_3	17.8 ± 0.2	0.2 ± 0.01	17.7 ± 0.2
[**1**][I$^-$]^d	*o*-CH_3	17.7 ± 0.2	−0.2 ± 0.01	17.7 ± 0.2
[**1**][Δ-**2**]^e	*o*-CH_3	18.0 ± 0.2	0.9 ± 0.01	17.7 ± 0.2
[**1**][Δ-**2**]^e	CH_3P^+	17.3 ± 0.2	1.1 ± 0.01	17.0 ± 0.2

^{a} kcal mol^{-1}. ^{b} cal mol^{-1} K^{-1}. ^{c} In DMSO-d_6, 300 MHz. ^{d} In toluene-d_8 (3% DMSO-d_6), 500 MHz. ^{e} In 17% DMSO-d_6/toluene-d_8, 500 MHz.

The activation parameters ($\Delta H^{\ddagger}$, $\Delta S^{\ddagger}$, and $\Delta G^{\ddagger}$) for the dynamic barriers of diastereotopic groups (atoms) exchange and of enantiomerization were calculated by using Arrhenius plots (1st order-kinetics, ln k vs $1/T$) and the Eyring equation. Values are reported in Table 1.[31] Virtually null activation entropy values have been found which is consistent with an intramolecular process.[32] From the activation parameters, values for $k_{exchange}$ and $k_{enantio}$ can be calculated at 298 K which are also in perfect agreement with the two-ring flip enantiomerization pathway (∼0.7 and ∼2.1 s^{-1}, respectively).

Conclusion

This work provides the first example of a supramolecular stereocontrol over the propeller geometry of a triarylalkylphosphonium cation, both in solution and in the solid state. The enantiomerization mechanism has been determined from the comparison of the rate of NMR exchange of diastereotopic atoms (groups) and the rate of enantiomerization measured in the presence of an NMR chiral solvating agent, this simple kinetic analysis being possibly extendable to other molecules racemizing by "correlated" rotations of aromatic rings.[21] Further studies involve the generalization of the supramolecular stereocontrol and theoretical calculations to evaluate and compare (in the absence of solvent and motion entropy) the activation parameters through the four possible pathways.[33]

Experimental Section

Methyl-tris(2,4,6-trimethyl-phenyl)-phosphonium Δ-Tris(tetrachlorobenzenediolato)phosphate or [1][Δ-2]. To a solution of [**1**][iodide] salt (30.0 mg, 0.057 mmol) in chloroform (2.1 mL) was added a solution of [cinchonidinium][Δ-**2**] salt (72.1 mg, 0.068 mmol, 1.2 equiv) in acetone (2.0 mL). The mixture was concentrated under reduced pressure, and the resulting salt was purified by pipet chromatography over basic alumina ($CHCl_3$, single eluted fraction) to give the titled compound as a white solid (64.2 mg, 97%).[31]P NMR (toluene-d_8, 203 MHz, maj/min[34] 2.3:1) δ 7.6 (P^+, maj), 7.3 (P^+, min), −79.9 (P^-). ^{1}H NMR (toluene-d_8, 500 MHz, maj/min 2.3:1): δ 6.69 (d, ^4J (H,H) = 3.2 Hz, 3H min), 6.55 (d, ^4J (H,H) = 3.2 Hz, 3H maj), 6.47 (d, ^4J (H,H) = 3.8 Hz, 3H min), 6.42 (d, ^4J (H,H) = 3.9 Hz, 3H maj), 3.09 (d, ^2J (P,H) = 10.9 Hz, 3H maj), 2.56 (d, ^2J (P,H) = 11.3 Hz, 3H min), 2.06 (s, 9H maj), 2.02 (s, 9H min), 1.96 (s, 9H maj), 1.93 (s, 9H min), 1.59 (s, 9H maj), 1.58 (s, 9H min). ^{13}C NMR ($CDCl_3$, 126 MHz): δ 145.6 (C, d, J (C,P) = 2.0 Hz), 145.4 (C, d, J (C,P) = 2.3 Hz), 143.8 (C, d, J (C,P) = 11.5 Hz), 143.7 (C, d, J (C,P) = 10.3 Hz), 143.5 (C, d, J (C,P) = 11.5 Hz), 143.1 (C, d, J (C,P) = 10.3 Hz), 142.1 (C, d, J (C,P) = 6.9 Hz, Δ-**2**), 133.4 (CH, d, J (C,P) = 11.5 Hz), 133.2 (CH, d, J (C,P) = 11.5 Hz), 133.1 (CH, d, J (C,P) = 11.5 Hz), 122.4 (C, Δ-**2**), 120.0 (C, d, J (C,P) = 79.2 Hz), 119.7 (C, d, J (C,P) = 79.2 Hz), 113.9 (C, d, J (C,P) = 19.5 Hz, Δ-**2**), 25.6 (P^+−CH_3, d, J (C,P) = 63.1 Hz), 25.5 (P^+−CH_3, d, J (C,P) = 63.1 Hz), 24.0 (CH_3, d, J (C,P) = 4.6 Hz), 23.9 (CH_3, d, J (C,P) = 5.7 Hz), 23.9 (CH_3, d, J (C,P) = 5.7 Hz), 23.8 (CH_3, d, J (C,P) = 4.6 Hz), 21.3 (CH_3). MS-ES: *m*/*z* (relative intensity) (+) 403.5 (100%); (−) 768.8 (100%), 113.5 (15%). ESI−HRMS: (+) calcd for $C_{28}H_{36}P$, (*m*/*z*) 403.2554; found, 403.2536; (−) calcd for $C_{18}Cl_{12}O_6P$, (*m*/*z*) 762.5695; found, 762.5705. IR: 3029, 2964, 2922, 2850, 1603, 1446, 1388, 1302, 1250, 1235, 990, 905, 817, 718, 670, 648, 641, 620 cm^{-1}; mp 185−188 °C; $[\alpha]^{20}_D$ −345 (*c* 0.1, toluene).

Methyl-tris(2,4,6-trimethyl-phenyl)-phosphonium Δ-Bis(tetrachlorobenzenediolato)mono((*S*)-1,1′-dinaphthyl-2,2′-diolato)-phosphate or [1][Δ-3]. To a solution of [**1**][iodide] salt (30.0 mg, 0.057 mmol) in chloroform (2.1 mL) was added a solution of [Me_2-NH_2][Δ-**3**] salt (57.8 mg, 0.068 mmol, 1.2 equiv) in acetone (2.0 mL). The mixture was concentrated under reduced pressure, and the resulting salt was purified by pipet chromatography over basic alumina ($CHCl_3$, single eluted fraction) to give the titled compound as a white solid (63.6 mg, 93%). ^{31}P NMR (toluene-d_8, 203 MHz, maj/min 2.8:1): δ 7.6 (P^+, maj), 7.3 ((P^+, min), −82.2 (P^-). ^{1}H NMR (toluene-d_8, 500 MHz, maj/min 2.8:1): δ 7.63 (d, ^3J (H,H) = 8.2 Hz, 2H), 7.41 (t, ^3J (H,H) = 8.3 Hz, 4H), 6.84 (t, ^3J (H,H) = 7.7 Hz, 2H), 6.68 (d, ^3J (H,H) = 8.7 Hz, 2H), 6.61 (d, 3H min), 6.35−6.33 (m, 6H maj + 3H min), 2.56 (d, ^2J (P,H) = 10.9 Hz, 3H maj), 2.28 (d, ^2J (P,H) = 10.9 Hz, 3H min), 1.90 (s, 9H min), 1.82 (s, 9H maj), 1.69 (s, 9H maj), 1.66 (s, 9H min), 1.49 (s, 9H maj), 1.44 (s, 9H min). ^{13}C NMR ($CDCl_3$, 126 MHz): δ 152.7 (C, d, J (C,P) = 12.6 Hz, Δ-**3**), 144.9 (C, d, J (C,P) = 3.4 Hz), 144.7 (C, d, J (C,P) = 2.3 Hz), 143.8 (C, d, J (C,P) = 11.5 Hz), 143.5 (C, d, J (C,P) = 11.5 Hz), 143.3 (C, d, J (C,P) = 10.3 Hz), 143.2 (C, d, J (C,P) = 10.3 Hz), 143.1 (C, d, J (C,P) = 5.7 Hz, Δ-**3**), 142.6 (CH, d, J (C,P) = 9.2 Hz, Δ-**3**), 133.2 (CH, d, J (C,P) = 11.5 Hz), 133.0 (CH, d, J (C,P) = 11.5 Hz), 132.7 (CH, d, J (C,P) = 11.5 Hz), 132.6 (CH, d, J (C,P) = 11.5 Hz), 132.5 (C, d, J (C,P) = 12.6 Hz, Δ-**3**), 130.5 (C, Δ-**3**), 128.9 (CH, Δ-**3**), 128.2 (CH, Δ-**3**), 127.2 (CH, Δ-**3**), 125.2 (CH, Δ-**3**), 123.9 (CH, Δ-**3**), 123.3 (CH, J (C,P) = 3.4 Hz, Δ-**3**), 123.2 (CH, J (C,P) = 3.4 Hz, Δ-**3**), 122.3 (C, Δ-**3**), 120.7 (C, Δ-**3**), 120.1 (C, d, J (C,P) = 79.2 Hz), 119.9 (C, d, J (C,P) = 79.2 Hz), 113.7 (C, J (C,P) = 19.5 Hz, Δ-**3**), 113.6 (C, J (C,P) = 18.4 Hz, Δ-**3**), 25.4 (P^+−CH_3, d, J (C,P) = 63.1 Hz), 25.3 (P^+−CH_3, d, J (C,P) = 63.1 Hz), 23.8 (CH_3, d, J (C,P) = 5.7 Hz), 23.6 (CH_3, d, J (C,P) = 4.6 Hz), 23.4 (CH_3, d, J (C,P) = 4.6 Hz), 21.2 (CH_3, s), 21.1 (CH_3, s); MS-ES: *m*/*z* (relative intensity) (+) 403.5 (100%); (−) 807.0 (100%), 113.4 (20%). ESI−HRMS: (+) calcd for $C_{28}H_{36}P$, (*m*/*z*) 403.2554; found, 403.2539; (−) calcd for $C_{32}H_{12}Cl_8O_6P$, (*m*/*z*) 802.7879; found, 802.7900. IR: 3028, 2970, 2915, 2855, 1603, 1594, 1456, 1451, 1387, 1334, 1304, 1230, 992, 953, 816, 670, 652, 610 cm^{-1}; mp 228−232 °C; $[\alpha]^{20}_D$ −115 (*c* 0.1, toluene).

Acknowledgment. We are grateful for financial support of this work by the Swiss National Science Foundation and the State Secretariat for Education and Science. We thank Prof. Hans J. Reich (University of Wisconsin, Madison) for providing a registered copy of WinDNMR.

Supporting Information Available: ^{1}H, ^{13}C, and ^{31}P NMR spectra of compounds [**1**][Δ-**2**] and [**1**][Δ-**3**], comparison of the ^{1}H NMR spectra of [**1**][I$^-$], [**1**][Δ-**2**], and [**1**][Δ-**3**], and stereodynamics of [**1**][I$^-$] and [**1**][Δ-**2**]. This material is available free of charge via the Internet at http://pubs.acs.org.

JO061097W

(31) The $k_{exchange}$ value is in perfect agreement with previous experiments (see ref 7).

(32) Unlike in the organometallic phosphane chemistry, an eventual dissociation−association enantiomerization pathway can essentially be ruled out.

(33) Lepetit, C.; Laleu, B.; Bernardinelli, G.; Lacour, J.; Chauvin, R., work in progress.

(34) maj and min identify signals from the major and minor conformers, respectively.