Factors Affecting Reaction Pathways in Nucleophilic Substitution Reactions on Platinum(II) Complexes: A Comparative Kinetic and Theoretical Study

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Kinetic studies in CH_2Cl_2 of the displacement of the thioethers from *cis*-$[PtPh_2(Et_2S)_2]$ with pyridine or substituted pyridines to yield *cis*-$[PtPh_2(py)_2]$ show, in agreement with previous findings, that the rate-determining step is dissociation of a molecule of thioether and the formation of a transient 3-coordinate $[Pt(Ph)_2(Et_2S)]$ intermediate. At 298.16 K, the rate constant for dissociation $k_1 = (2.12 \pm 0.1) \times 10^{-3}$ s^{-1}, $\Delta H^* = 99.9 \pm 1$ kJ mol^{-1} and $\Delta S^* = +39 \pm 4$ J mol^{-1} K^{-1}. In contrast, the complex *cis*-$[PtPh_2(CO)(Et_2S)]$, in the same reactions and under the same experimental conditions, undergoes substitution of Et_2S only through a bimolecular pathway, showing a considerable discrimination among various nucleophiles. In the reaction with pyridine, the second-order rate constant $k_2 = 30.0 \pm 0.1$ M^{-1} s^{-1}, $\Delta H^* = 34 \pm 1$ kJ mol^{-1}, $\Delta S^* = -174 \pm 4$ J mol^{-1} K^{-1}. Extended Huckel theory (EHT) and molecular electrostatic potential (MEP) calculations were performed on molecules of the type *cis*-$[PtCl_2S_2]$, *cis*-$[PtMe_2S_2]$, and *cis*-$[PtMe_2(CO)S]$ (S = Me_2S or Me_2SO), searching for a correlation between electronic properties and pathways followed for substitution. The sharp changeover of mechanism (dissociative vs. associative) observed on going from the diaryl disulfide to the diaryl carbonyl sulfide platinum(II) complex, is accounted for by the presence on the latter of a LUMO perpendicular to the plane, suitable to the nucleophilic attack, and by a large positive electronic potential. Dissociation is a combined result of ground-state destabilization and of a concurrent increase of electron density at the metal, preventing the approach of nucleophiles.

Introduction

During the last three decades, substitution reactions on square planar complexes have been studied in great detail from a mechanistic point of view.[1] The mechanistic picture nowadays appears to be reasonably clear, and it involves the direct attack of the nucleophile on the substrate with the formation of a transient five-coordinate intermediate. The rate of substitution will depend on many factors, and among them the nature of the metal, of the trans group, and of the reagent group seems to play the major role in a mutual and rather intricate interaction.[2] Usually the substrate shows a considerable discrimination among different nucleophiles. Many efforts are devoted nowadays to investigate the details of the intimate mechanism in terms of the synchronism and the relative importance of bond making and bond breaking in reaching the transition state.

Dissociative substitutions are a rarity.[3] We had the first evidence for ligand dissociation as the dominant pathway studying the kinetics of replacement of both sulfides or sulfoxides by nitrogen chelating ligands (L-L) in some platinum(II) complexes of the type *cis*-$[PtR_2S_2]$ (R = Me or Ph; S = R_2S or Me_2SO) to yield $[PtR_2(L\text{-}L)]$ products in nonpolar solvents.[4] The facile dissociation was thought to derive essentially from the strong σ-donor power of the trans Me or Ph groups, which lengthen and weaken the Pt–S bond. Indeed, strictly similar classical coordination compounds having chloride instead of an alkyl or aryl group and a shorter Pt–S bond distance, such as *cis*-$[PtCl_2(Me_2S)_2]$[5] and *cis*-$[PtCl_2(Me_2SO)_2]$,[6] are known to undergo substitution by way of the normal associative mode of activation. Compounds such as $[Pt(en)(Me_2SO)_2]^{2+}$ [7] (en = 1,2-diaminoethane) and $[Pt(Me_2SO)_4]^{2+}$ [8] behave likewise.

In principle, ground-state destabilization could not be sufficient by itself to produce a changeover of mechanism, since weakening of the leaving group should also have the effect of increasing the rate of an associative pathway. Thus, we started to wonder whether other concurrent factors could be important and decided to exploit the unique opportunity offered by these systems of comparing dissociative and associative processes, searching for a correlation between mechanism and structural changes imposed on the substrates. In this paper we have carried out a comparative kinetic and theoretical study of substrates of the type *cis*-$[PtR_2S_2]$, *cis*-$[PtCl_2S_2]$, and *cis*-$[PtR_2(CO)S]$ (R = Me or Ph; S = R_2S or Me_2SO). In these latter species, the Pt–S bond is still under the strong trans influence of an R group, but the bound carbonyl exerts all the features of a π-acceptor ligand and the metal

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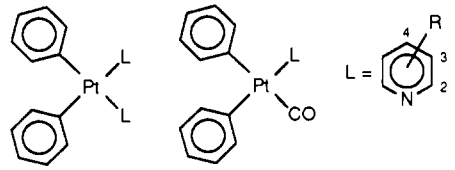
Table I. Relevant ^{1}H NMR data of the complexes *cis*-$[Pt(C_6H_5)_2(L)_2]$(I) and *cis*-$[Pt(C_6H_5)_2(CO)L]$(II)[a,b]



I II

compound	δ(ligand) H_2	H_3	H_4	Me	δ(Pt aryl)
I (L = py)	8.50 (6.5;[c] 29.2[d])		7.75 (7.6)		6.84
I (L = 4-Mepy)	8.31 (5.0; 19.2)			2.30	6.83–7.03
I (L = 4-Me_2Npy)	7.98 (5.7; 24.4)	6.30 (5.7)		2.98	6.82–7.07
I (L = 2-Mepy)				2.84[e]	7.47
II (L = py)	8.68 (6.4; 22.0)		7.83 (7.6)		6.98
II (L = 4-Mepy)	8.49 (6.7; 22.0)			2.39	7.17–7.37
II (L = 4-Me_2Npy)	8.11 (5.9; 21.7)	6.42 (5.8)		3.02	6.96–7.39
II (L = 2-Mepy)	8.78 (5.6; 21.1)			2.94	6.99

[a] In $CDCl_3$ as solvent. [b] δ in ppm from TMS as internal reference. [c] Coupling constant in Hz. [d] $^3J_{PtH}$ in Hz. [e] $^3J_{PtH}$ = 4.9 Hz.

possesses a vacant low-energy orbital suitable for nucleophilic attack. The kinetic results, the EHT calculations, and the MEP analysis on these compounds all concur to indicate that changes of electronic density at the metal center on changing ligands play a major role in dictating the choice of the reaction pathways.

Experimental Section

***cis*-Diphenylbis(diethyl sulfide)platinum(II) and *cis*-diphenylcarbonyl(diethyl sulfide)platinum(II)** were prepared by following essentially the same procedure described in the literature.[4f,9] The spectroscopic properties of the compounds obtained (UV spectra, IR stretching frequencies, ^{1}H and ^{13}C resonances) were exactly the same as those reported in the literature. The elemental analysis was consistent with the theoretical formulas. The reaction of the first compound with a sufficient excess of pyridine or of substituted pyridines led to the substitution of both the coordinated sulfide groups and to the formation of compounds of the type *cis*-$[PtPh_2(py)_2]$. The reaction of *cis*-$[PtPh_2(CO)Et_2S]$ with the same reagents yielded compounds of the type *cis*-$[PtPh_2(CO)(py)]$. Except for the case of the compounds with pyridine as ligand, these reaction products were not isolated as solid compounds but were characterized in solution through their ^{1}H NMR spectra. Because of the multiplicity and superposition of most peaks, only some of the resonances of the coordinated ligands are reported in Table I. Anal. Calcd for *cis*-$[PtPh_2(py)_2]$, $C_{22}H_{20}N_2Pt$: C, 52.07; H, 3.97; N, 5.52. Found: C, 51.98; H, 4.03; N, 5.60. Anal. Calcd for *cis*-$[PtPh_2(CO)(py)]$, $C_{18}H_{15}NOPt$: C, 47.37; H, 3.31; N, 3.07. Found: C, 47.51; H, 3.40; N, 3.15.

Infrared spectra were taken on a Perkin-Elmer Model FT 1720 X instrument; ^{1}H NMR spectra were recorded at 200 MHz on a Bruker WP 200 spectrometer. Chemical shifts are reported in parts per million downfield from Me_4Si. Microanalysis were performed by Analytical Laboratories, Engelskirchen, Germany. All reactions involving organometallic compounds were carried out under prepurified nitrogen or welding-grade argon using standard techniques for handling air-sensitive compounds. Ethereal solvents were dried by distillation from disodium benzophenone dianion. Methylene chloride for use in kinetic runs was distilled from barium oxide under nitrogen and then redistilled through 60-cm platinum spinning band column, collecting the center cut for use. Pyridines and substituted pyridines were commercial materials, purified by recrystallization or distillation as necessary.

Theoretical Calculations. Theoretical calculations and MEP (molecular electrostatic potentials) studies on the series of compounds *cis*-$[PtCl_2(SMe_2)_2]$ (**1**), *cis*-$[PtMe_2(SMe_2)_2]$ (**2**), and *cis*-$[PtMe_2(CO)(SMe_2)]$ (**3**) and related sulfoxide derivatives *cis*-$[PtCl_2(Me_2SO)_2]$ (**4**), *cis*-$[PtMe_2(Me_2SO)_2]$ (**5**) and *cis*-$[PtMe_2(CO)(Me_2SO)]$ (**6**) were performed. The theoretical calculations were performed using the simple EHT (extended Huckel theory) method. The EHT program, written using standard parameters H_{ij} developed by Hoffmann,[10] was linked with a minimization subroutine to optimize the starting geometries of the compound. For all the molecules the starting geometries were obtained from crystallographic data[11] or by using standard values for strictly similar compounds.[12] The geometry optimization was performed on the angular variables, bond and torsional angles, keeping constant the distances between the atoms. In all the cases, the final geometries did not differ appreciably from the starting values, showing that for these molecules there are not strong intermolecular interactions in the solid state and that the geometries are determined essentially by intramolecular factors.

The MEP analysis was performed by using a standard procedure.[13] According to Scrocco and Tomasi,[14] the electrostatic interaction energy of a positive point charge, located in **r**, with an undistorted substrate is given within the LCAO framework by

$$V_e(r) = \sum_A \frac{Z_A}{|r - r_A|} - \sum_{\mu,\sigma} P_{\mu\sigma}\langle\mu|1/r|\sigma\rangle \qquad (1)$$

where the first term corresponds to nuclear repulsion, the summation running over all atoms A of the substrate with nuclear charge Z_A and located at r_A. The second term originates from the electronic attraction, $P_{\mu\sigma}$ being the first-order density matrix element corresponding to atomic orbitals μ and σ, and $\langle\mu|1/r|\sigma\rangle$ being defined as

$$\langle\mu|1/r|\sigma\rangle = \int \phi_\mu(r')\frac{1}{|r - r'|}\phi\sigma(r')\,dr' \qquad (2)$$

This integral represents the elecrostatic attraction between an electron located in the AOs $\phi_\mu\phi_\sigma$ and the incoming positive charge. In the case of nucleophilic addition reaction $V_n(\mathbf{r})$ is obtained simply by changing the signs of $V_e(\mathbf{r})$, i.e. $V_n(\mathbf{r}) = -V_e(\mathbf{r})$, or by considering that the areas in the map with negative values are favorable for electrophilic attack and are not favorable for nucleophilic attack and vice versa.

We have also used the general approximation to calculate the $\langle\mu|1/r|\sigma\rangle$ term.[13,15,16] Using the Mulliken approximation,[17] this term can be rewritten as

$$\langle\mu|1/r|\sigma\rangle = (1/2)S_{\mu\sigma}[\langle\mu|1/r|\mu\rangle + \langle\sigma|1/r|\sigma\rangle] \qquad (3)$$

which, inserted in eq 1, leads to the expression

$$V_e(r) = \sum_A \frac{Z_A}{|r - r_A|} - \sum_{\mu,\sigma}(1/2)P_{\mu\sigma}S_{\mu\sigma}[\langle\mu|1/r|\mu\rangle + \langle\sigma|1/r|\sigma\rangle] \qquad (4)$$

Kinetics. Slower reactions were started by mixing known volumes of prethermostated standard solutions of reagents in the thermostated (±0.05 °C) cell compartment of a Cary 219 or a Perkin-Elmer Lambda 5 spectrophotometer and followed by repetitive scanning of the spectrum at suitable times in the visible and near-UV region or at a fixed wavelength, where the difference of absorbance was largest. Faster reactions required the use of a rapid-scanning Hewlett-Packard Model 8452 A spectrophotometer. The use of at least a 10-fold excess of nucleophile over complex ensured first-order kinetics in any run. All the reactions obeyed a first-order rate law until well over 90% reaction and the rate constants k_{obsd} (s^{-1}) were obtained either graphically or from a nonlinear least-squares fit of the experimental data to $A_t = A_\infty + (A_0 - A_\infty)\exp(-k_{obsd}t)$ with A_0, A_∞, and k_{obsd} as the parameters to be optimized (A_0 = absorbance after mixing of reagents; A_∞ = absorbance at completion of reaction). Activation parameters were derived from a linear least-square analysis of ln (k/T) vs T^{-1} data.

Results

(a) Substitution Reactions. The reaction of *cis*-$[PtPh_2(Et_2S)_2]$ with a sufficient excess of pyridine (py) or of substituted pyridines (4-methylpyridine, 4-Mepy; 2-methylpyridine, 2-Mepy; and 4-(dimethylamino)pyridine, 4-Me_2Npy) led to the substitution

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Table II. First Two Unoccupied and Last Five Occupied Molecular Orbitals, Relative Energies, and Principal Percent Contributions from the AO for the Thioether Compounds **1–3**

	MO no.	energy eV	principal % contribns of AO
			$[PtCl_2(Me_2S)_2]$ (**1**)
	34	−4.861	Pt, p_z = 91.6
LUMO	33	−7.531	Pt, x^2-y^2 = 73.8; S1, p_x = 17.6; S2, p_y = 17.1; Cl1, p_x = 14.2; Cl2, p_y = 14.2
HOMO	32	−11.516	Pt, xy = 66.6; S1, p_y = 12.0; S2, p_x = 12.2
	31	−11.783	Pt, xz = 10.7, yz = 11.3; S1, p_y = 26.7; S2, p_x = 27.2
	30	−12.149	Pt, xz = 40.0, yz = 37.8, xy = 8.2; Cl1, p_z = 7.5; Cl2, p_z = 7.5
	29	−12.343	Pt, s = 5.3, d_{z^2} = 91.5
	28	−12.366	Pt, xz = 33.1, yz = 35.0; S1, p_y = 7.6; S2, p_x = 7.8
			$[PtMe_2(Me_2S)_2]$ (**2**)
	34	−5.233	Pt, p_z = 90.2
LUMO	33	−6.407	Pt, x^2-y^2 = 65.1; Me1, p_x = 27.3; Me2, p_y = 27.2; S1, p_x = 13.6; S2, p_y = 13.9
HOMO	32	−11.576	Pt, xy = 53.0; S1, p_y = 15.9; S2, p_x = 15.3
	31	−11.856	Pt, xz = 8.7, yz = 7.3; S1, p_y = 25.4, p_z = 5.8; S2, p_x = 25.2, p_y = 5.6, p_z = 5.4
	30	−12.223	Pt, s = 7.6, d_{z^2} = 79.4
	29	−12.388	Pt, xz = 37.1, yz = 45.2, xy = 12.6
	28	−12.490	Pt, xz = 42.6, yz = 36.2
			$[PtMe_2(CO)(Me_2S)]$ (**3**)
	29	−9.261	Pt, xy = 10.2; C(carb), p_x = 89.7; O, p_x = 25.7 {antibond: $p_x(C_{carb}) - p_x(O)$ = −10.3}
LUMO	28	−9.552	Pt, yz = 11.1; C(carb), p_z = 80.8; O, p_z = 24.9 {antibond: $p_z(C_{carb}) - p_z(O)$ = −9.6}
HOMO	27	−11.727	Pt, xz = 8.0, xy = 27.9; S, p_y = 47.2; p_z = 7.1
	26	−12.220	Pt, s = 7.5, d_{z^2} = 77.2
	25	−12.418	Pt, xz = 79.6, xy = 14.2
	24	−12.643	Pt, yz = 86.0
	23	−12.838	Pt, xz = 6.7, xy = 36.5; Me2, p_y = 7.9; S, p_y = 13.8

of both the coordinated sulfide groups according to

$$cis\text{-}[PtPh_2(Et_2S)_2] + 2L \rightarrow cis\text{-}[PtPh_2L_2] + 2\,Et_2S \quad (5)$$

When equimolar solutions of the *cis*-$[PtPh_2(Et_2S)_2]$ complex and of the pyridine nucleophile are mixed, the ^1H NMR spectrum of the final reaction mixture shows signals assigned to unreacted *cis*-$[PtPh_2(Et_2S)_2]$, monosubstituted *cis*-$[PtPh_2(Et_2S)(L)]$, and bissubstituted *cis*-$[PtPh_2L_2]$, in a ratio dependent on the nature of the pyridine used. In the presence of excess of free ligand (at least in a ratio of 1:5) only peaks due to the free ligands and to the final *cis*-$[PtPh_2L_2]$ complex are observed. Under these circumstances there is no evidence for the buildup in solution of any other intermediate species containing thioether coordinated to the metal, and the substitution reaction goes to completion. Thus, the course of the reaction can be effectively monitored by means of ^1H NMR spectroscopy, through the decrease of the signals due to the bound Et_2S in *cis*-$[PtPh_2(Et_2S)_2]$ (a multiplet at 2.53 ppm and a triplet at 1.32 ppm, in deuterated chloroform) and the parallel matching increase of the signals of the free Et_2S (a 1:3:3:1 quartet at δ 2.55 together with a 1:2:1 triplet centered at δ 1.26). Since to perform a fine kinetic analysis we need well-separated signals, those of the bound and free pyridines appear to be less useful to the purpose. For example, when 4-(dimethylamino)pyridine is used as a reagent in $CDCl_3$, the methyl signal of the free ligand at 3.00 ppm, upon coordination in *cis*-$[PtPh_2(4\text{-}Me_2Npy)_2]$, moves only to a value of δ = 2.98 ppm. The kinetic study was carried out in CH_2Cl_2 and followed spectrophotometrically. The reactions were carried out under pseudo-first-order conditions, in the presence of a sufficient and known excess of entering ligand and of free diethyl sulfide. An abstract factor analysis of the spectral changes[18] was consistent with the presence of only two absorbing species in solution, the starting complex and the final *cis*-$[PtPh_2L_2]$ product, confirming that the intermediate monosubstituted species is very labile in solution. The values of the rate constants, k_{obsd}, are available as supplementary material (Table SI), where they are compared with k_{calcd} from the derived rate constants.

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The reactions

$$cis\text{-}[PtPh_2(CO)(Et_2S)] + L \rightarrow cis\text{-}[PtPh_2(CO)(L)] + Et_2S \quad (6)$$

where L = py, 4-Mepy, 2-Mepy, and 4-Me_2Npy, were carried out in dichloromethane as solvent. The analysis of the changes of the ^1H NMR signals assigned to the protons of the coordinated and uncoordinated L and Et_2S ligands during the course of the reaction showed that the process under study was indeed the simple substitution of the bound thioether with L. The carbonyl group remains firmly bound to the metal, as shown by the observation of its stretching frequency by IR spectroscopy. The systematic kinetics of this reaction were studied at different ligand concentrations within the range 0.01–0.4 M and were followed spectrophotometrically. The pseudo-first-order rate constants, k_{obsd} (listed in Table SII), were linearly dependent on ligand concentration, fitting the rate law $k_{obsd} = k_2[L]$. This linear plots passed through the origin within the limits of experimental error. Addition of large amounts of free sulfide did not produce any mass-law retardation.

(b) Theoretical Calculations. The theoretical calculations were performed using the simple EHT (Extended Huckel Theory) method. The results of theoretical calculations are reported in Tables II and III, where the highest five occupied (OMO) and the lowest two unoccupied (UMO) molecular orbitals are listed, together with the relative energies (in eV) and the major percent contributions from the atomic orbitals.

A recent paper by Weber et al.[16] has shown that intermolecular energies and relative MEP calculated in the framework of the extended Huckel theory compare well with those obtained from more sophisticated ab initio calculations. The MEP analysis for all the compounds was performed at large distances of the substrate, 10 au (≈5.3 Å) on the z axis perpendicular to the plane of the molecule. This choice was dictated by the consideration that the nucleophilic (electrophilic) agent is not a negative (positive) point charge. Therefore, when it interacts with the substrate, the MEP is greatly modified with respect to the MEP of the isolated substrate, because of the interactions between the nucleophilic-substrate orbitals. Then, in general it is needed to calculate the MEPs at several distances (and orientations) of nucleophilic substrate molecules. But, in our case, the experimental evidence shows that the choice of the reaction mechanism (dissociative or associative) is almost independent of the nature

Table III. First Two Unoccupied and Last Five Occupied Molecular Orbitals, Relative Energies, and the Principal Percent Contributions from the AO for the Sulfoxide Compounds **4–6**

	MO no.	energy, eV	principal % contribs of AO
			$[PtCl_2(Me_2SO)_2]$ (**4**)
	40	−4.995	Pt, p_z = 87.4
LUMO	39	−7.074	Pt, $x^2 - y^2$ = 69.8; S1, p_y = 18.2; S2, p_x = 18.0; Cl1, p_x = 14.8; Cl2, p_y = 14.8
HOMO	38	−12.035	Pt, xy = 83.1; Cl1, p_y = 8.6; Cl2, p_x = 8.7
	37	−12.135	Pt, xz = 41.1, yz = 44.0; Cl1, p_z = 8.1; Cl2, p_z = 8.1
	36	−12.187	Pt, xz = 45.0, yz = 42.0; Cl1, p_z = 5.9; Cl2, p_z = 5.9
	35	−12.320	Pt, s = 6.0; d_{z^2} = 86.5
	34	−12.789	Cl1, p_x = 5.8, p_y = 27.1; Cl2, p_x = 26.2; p_y = 6.7; S1, p_y = 5.2; S2, p_x = 5.1; O1, p_y = 6.8; O2, p_x = 6.6
			$[PtMe_2(Me_2SO)_2]$ (**5**)
	40	−5.385	Pt, p_z = 88.4
LUMO	39	−6.183	Pt, $x^2 - y^2$ = 63.3; Me1, p_x = 26.4; Me2, p_y = 26.4; S1, p_y = 15.6; S2, p_x = 15.6
HOMO	38	−12.211	Pt, s = 8.1; d_{z^2} = 79.8
	37	−12.332	Pt, xz = 12.9, yz = 13.5; xy = 64.2
	36	−12.401	Pt, xz = 31.9, yz = 33.5; xy = 29.5
	35	−12.410	Pt, xz = 47.8, yz = 45.6
	34	−12.709	Me1, p_x = 12.3; Me2, p_y = 12.3; S1, p_y = 9.8; S2, p_x = 9.8; O1, p_y = 8.3; O2, p_x = 8.2
			$[PtMe_2(CO)(Me_2SO)]$ (**6**)
	32	−9.563	Pt, xz = 10.4; C(carb), p_z = 81.9; O, p_z = 25.2 {antibond: $p_z(C_{carb}) - p_z(O)$ = −9.8}
LUMO	31	−10.271	Me1, p_x = 5.1; C(carb), p_x = 38.3, p_y = 27.4; O, p_x = 25.4, p_y = 11.2
HOMO	30	−12.207	Pt, s = 7.8, d_{z^2} = 76.3; Me1, p_x = 5.7
	29	−12.313	Pt, yz = 11.8, xy = 74.7
	28	−12.354	Pt, yz = 71.4, xy = 13.1
	27	−12.577	Pt, p_y = 6.5; Me2, p_y = 19.9; S1, p_y = 15.9; O1, p_y = 15.0
	26	−12.622	Pt, xz = 84.7; O2, p_z = 5.1

of the nucleophile. Consequently, the factors determining the reaction pathway depend only on the nature of the substrate; i.e., they are intrinsic properties of the substrate. Thus, we have calculated the electrostatic potential surrounding the molecule in the unperturbed state and in the most stable conformation as calculated in the EHT approximation, to see whether or not this molecule displays a state favorable to nucleophilic attack. The MEP maps of all the compounds are shown in Figure 1.

Discussion

The isolation and characterization of some of the reaction product as a bissubstituted complex and the analysis of the ^1H NMR and electronic spectra suggest that reaction 5 proceeds according to two consecutive steps.

$$cis\text{-}[PtPh_2(Et_2S)_2] + L \xrightarrow{\text{slow}} cis\text{-}[PtPh_2(Et_2S)L] + Et_2S \quad (5')$$

$$cis\text{-}[PtPh_2(Et_2S)L] + L \xrightarrow{\text{fast}} cis\text{-}[PtPh_2L_2] + Et_2S \quad (5'')$$

The rate-determining step is therefore the displacement of the first thioether group. As found previously for this complex and for similar *cis*-$[PtR_2L_2]$ (R = Me, Ph; L = Me_2SO, R_2S) systems[4] in their reactions with the nitrogen chelating ligand 2,2′-bipyridine, the displacement of the thioether is retarded by addition of the free leaving group. The pseudo-first-order rate constants k_{obsd} (Table SI), when plotted against the concentration of the nucleophile at constant concentration of sulfide, give a curvilinear dependence, which levels off to a limiting value at high nucleophile concentration. A global 3-D representation of the L and Et_2S dependencies for the kinetic data of reaction 5 (L = pyridine) in dichloromethane at 298.16 K is given in Figure 2 and the representation of typical saturation plots for the reactivity of various reagents at $[Et_2S]$ = 0.00125 M is given in Figure 3.

The rate data appear to fit the rate law

$$k_{obsd} = a[L]/(b[Et_2S] + [L]) \quad (7)$$

The best values of the constants a and b, together with their standard deviations, were obtained by means of a nonlinear least-squares curve-fitting program.

All this evidence can be accomodated by the stepwise mechanism shown in Scheme I, which involves dissociation of the starting complex (via k_1) to yield a 14-electron $[PtPh_2(Et_2S)]$ intermediate. This latter can undergo the reentry of the leaving group (k_{-1} path) or can take up the entering ligand L (k_3 path) to form the transient $[PtPh_2(Et_2S)(L)]$ species. There follows fast displacement of the second molecule of Et_2S to yield the observed products. The rate constants are related to the empirical parameters a and b by the expressions $a = k_1$ and $b = k_{-1}/k_3$. Values of these rate constants are collected in Table IV. For all the reagents the dissociative route is the only one operative and there is no evidence of the contribution of a bimolecular pathway to the overall rate, even at higher nucleophile concentrations. As expected for a dissociative mechanism, the value of k_1 is constant and independent of the nature of the entering ligand, being centered at $(2.12 \pm 0.1) \times 10^{-3}$ s^{-1} at 298.16 K. The temperature dependence of k_1 in the reaction of *cis*-$[PtPh_2(Et_2S)_2]$ with pyridine gives $\Delta H^{\ddagger}$ = 99.9 ± 1 kJ mol^{-1} and $\Delta S^{\ddagger}$ = +39 ± 4 J mol^{-1} K^{-1} (Table IV). The large positive value of the entropy of activation gives strong support to the assumption of ligand dissociation as the dominant pathway. The general pattern of behavior is much the same as that found in our previous studies on this complex[4f] and on strictly similar systems,[4] where the easy dissociation of thioethers or sulfoxides was thought to be due to the strong σ-donor power of the trans Pt–C bond.

As described above, reaction 6 proceeds in a single step. In this case the displacement of the sulfide with pyridines is perfectly in keeping with the associative mode of activation usually found for substitution reactions on square planar complexes. As can be seen in Figure 4, the pseudo-first-order rate constants, when plotted against the concentration of the nucleophile, give straight lines with zero intercept, indicating that the usual two-term rate equation is obeyed

$$k_{obsd} = k_1 + k_2[L] \quad (8)$$

with the k_1 term making little if any contribution to the reactivity (k_1 arises from a solvolytic or a dissociative path, and k_2 is the second-order rate constant for bimolecular attack of L on the substrate). The values of k_2, from linear regression analysis of the rate law, are collected in Table IV (uncertainties are standard errors of estimates). As expected for a bimolecular process, in which bond making of the donor atom with the metal is particularly important, the *cis*-$[PtPh_2(CO)(Et_2S)]$ complex exhibits a considerable discrimination towards different entering groups. It is possible to see that the rates increase with increasing electron-donating ability of the substituents on the pyridine ring, followin

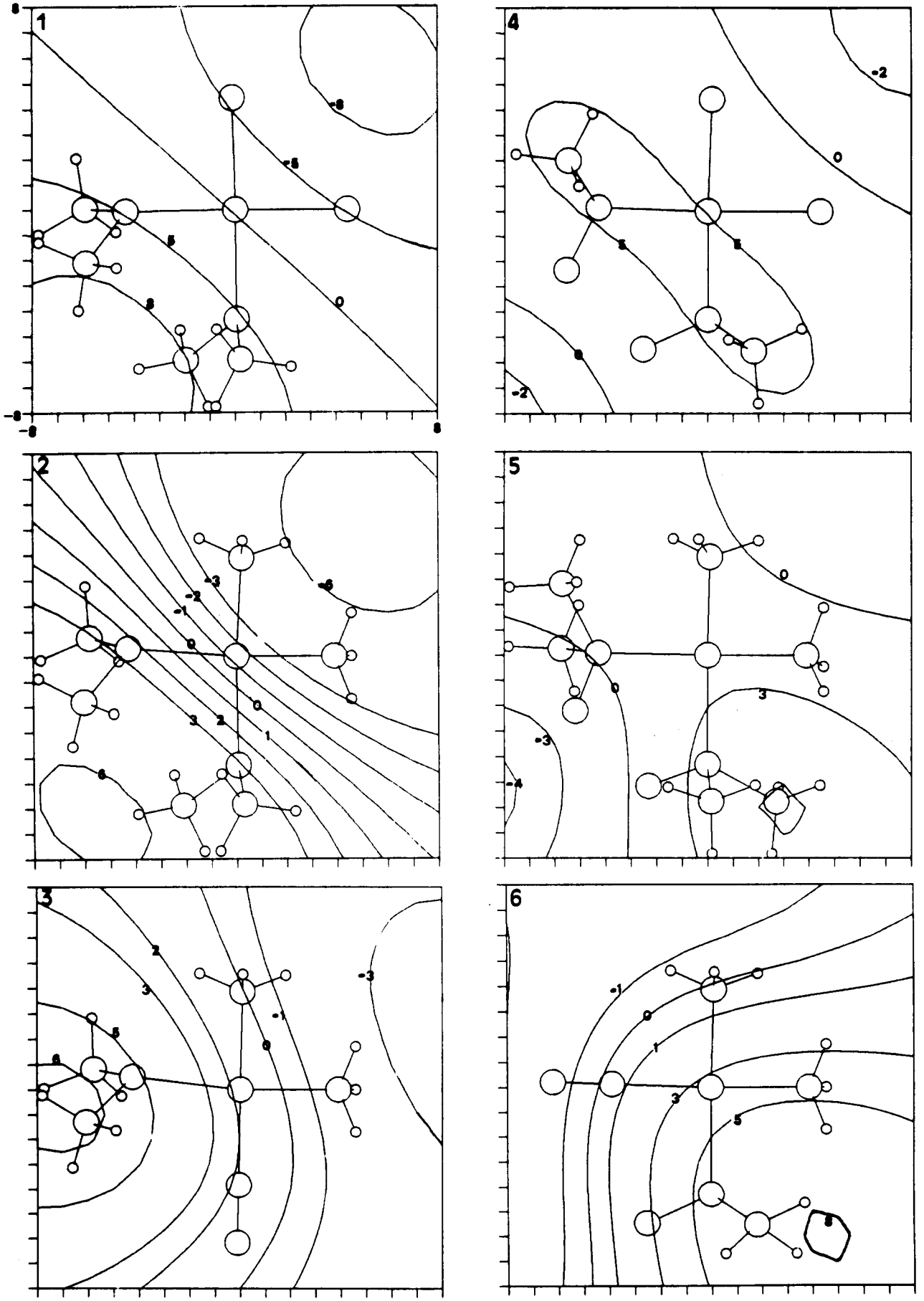

Figure 1. MEP maps of the sulfide compounds *cis*-[$PtCl_2(SMe_2)_2$] (**1**), *cis*-[$PtMe_2(SMe_2)_2$] (**2**), and *cis*-[$PtMe_2(CO)(SMe_2)$)] (**3**) and of the related sulfoxide derivatives *cis*-[$PtCl_2(Me_2SO)_2$] (**4**), *cis*-[$PtMe_2(Me_2SO)_2$] (**5**), and *cis*-[$PtMe_2(CO)(Me_2SO)$] (**6**).

the sequence of nucleophilicity 4-Me_2Npy > 4-Mepy > py ≫ 2-Mepy. The very low reactivity of this latter reagent stems from the significant amount of steric congestion produced in the transition state by the methyl substituent in the 2,6-positions[19]

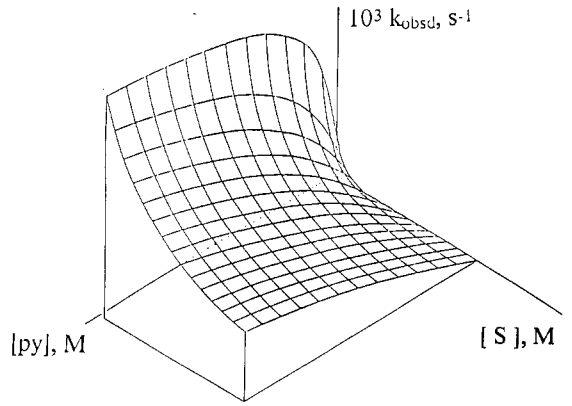

Figure 2. 3-D representation of the [Et_2S] and [py] dependencies for the reaction of *cis*-[$PtPh_2(Et_2S)_2$] with pyridine at 298.16 K.

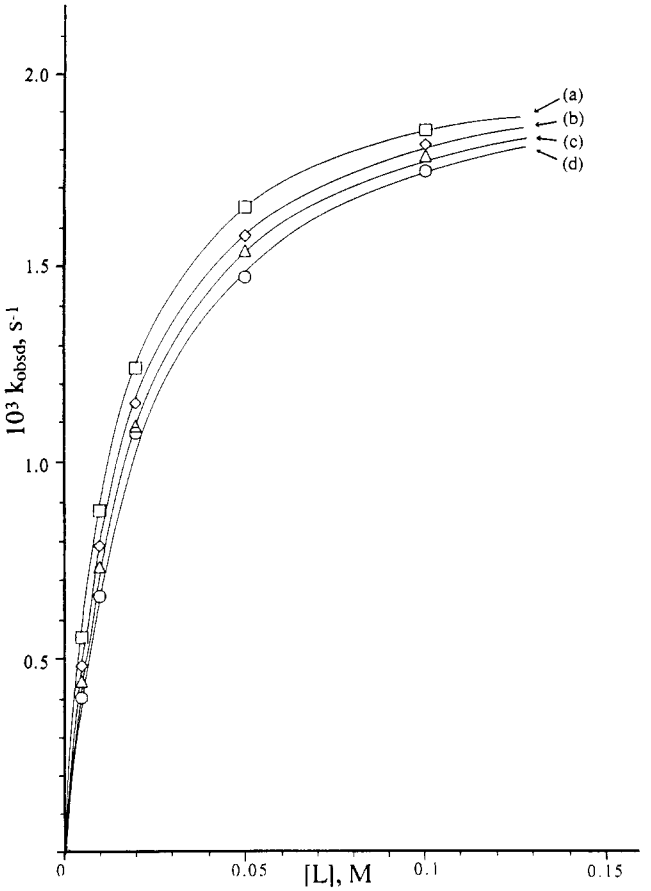

Figure 3. Dependence of the pseudo-first-order rate constants k_{obsd} (s^{-1}) on the concentration of the entering ligand for the reaction of *cis*-[$PtPh_2(Et_2S)_2$] with various reagents at 298.16 K in dichloromethane solution: (a) 2-Mepy; (b) 4-Me_2Npy; (c) 4-Mepy; (d) py. [Et_2S] = 0.0125 M.

with respect to those in the 3,5-positions or 4-position on the pyridine ring. The temperature dependence of k_2 in the reaction of *cis*-[$PtPh_2(CO)(Et_2S)$] with pyridine, as expected for an associative process, gives a low value of enthalpy of activation ($\Delta H^{\ddagger} = 34 \pm 1$ kJ mol^{-1}) and a large negative entropy of activation ($\Delta S^{\ddagger} = -174 \pm 4$ J mol^{-1} K^{-1}) (Table IV).

Summing up, dissociation is the prevalent reactivity pathway for *cis*-[$PtPh_2(Et_2S)_2$], even in the presence of a large excess of nucleophile, and it is not the result of the suppression of the normal associative pathway. Introduction of a carbonyl group as a spectator ligand in the coordination sphere, in place of one of the two thioethers, leads to a sharp changeover of mechanism. The substitution proceeds only through an associative pathway.

(19) Cattalini, L. The Initimate Mechanism of Replacement in d^8 Square-Planar Complexes. In *Inorganic Reaction Mechanisms*, Edwards, J. O., Ed.; Wiley: New York, 1970; Part I, pp 263–327.

Scheme I

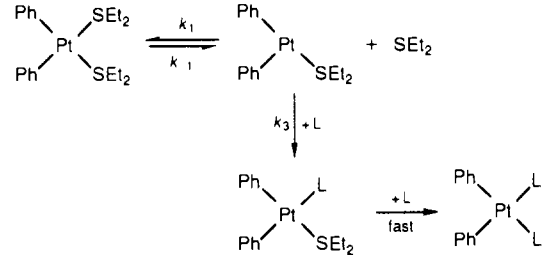

Table IV. Derived Rate Constants for the Reactions of *cis*-[$Pt(C_6H_5)_2(Et_2S)_2$] and *cis*-[$Pt(C_6H_5)_2(CO)(Et_2S)$] with Pyridines in Dichloromethane at 298.16 K

cis-[$Pt(C_6H_5)_2(Et_2S)_2$]

L	10^3k_1, s^{-1}	k_3/k_{-1}
py[a]	2.15 ± 0.01	0.57 ± 0.01
2-Mepy	2.11 ± 0.01	0.89 ± 0.02
4-Mepy	2.12 ± 0.01	0.66 ± 0.01
2,6-Me_2py	2.12 ± 0.01	0.74 ± 0.01

cis-[$Pt(C_6H_5)_2(CO)(Et_2S)$]

L	10^4k_1, s^{-1}	10^3k_2, M^{-1} s^{-1}
2-Mepy	*c*	4.90 ± 0.01
py[b]	*c*	30.0 ± 0.1
4-Mepy	*c*	59.0 ± 0.1
4-Me_2Npy	*c*	160 ± 1

[a] $\Delta H^{\ddagger} = 99.9 \pm 1$ kJ mol^{-1} and $\Delta S^{\ddagger} = +39 \pm 4$ J mol^{-1} K^{-1}. [b] $\Delta H^{\ddagger} = 34 \pm 1$ kJ mol^{-1} and $\Delta S^{\ddagger} = -174 \pm 4$ J mol^{-1} K^{-1}. [c] Not determined.

What is extremely important also is that there is not a significant parallel dissociative pathway; i.e., the dissociative pathway has been suppressed. We failed in our attempts to grow crystals of *cis*-[$PtPh_2(CO)(Et_2S)$] suitable for a X ray diffraction study. It would have been interesting to measure the distance of the platinum–thioether bond and to compare the value with that of the bis(sulfide) complex. However, we do not expect a significant difference, since the bond axis Ph–Pt–S is the same in both complexes and the Pt–S distance is mainly determined by the strong trans influence of the σ-donor phenyl group.[20] Strong support to this comes from the identity of ^3J(PtH) of the methylene group of the bound thioether in the two compounds. Thus, if we assume that the platinum–thioether bond is lengthened and weakened at the same extent in the two complexes, one is lead to conclude that while the presence of one or more Pt–C σ bonds helps dissociation, this ground-state destabilization cannot be the only or the prevalent factor dictating the reaction pathway, since changes of electron density at the metal must be taken into account.

At this stage it is worth discussing the results of the theoretical calculations. As pointed out in several works,[14,15] the MEP analysis is thought to be a powerful method to explain the reactivity of several organometallic compounds and can be in general very useful in kinetic studies, although several complex factors can concur to determine the mechanism of the substitution reaction (nucleophilic or electrophilic) as, for instance, dynamics which can affect the geometries and the electronic structures of the transient intermediates. A description of the potential surrounding the molecule and of the similarities or differences within a series of compounds can help in interpreting the way chosen by the substrate to react. The data in Tables II and III show that in all the compounds three of the highest five OMOs are always "pure" atomic orbitals of the platinum atom. This is in agreement with a previous work[21] performed on dimethylplatinum(II)

(20) Appleton, T. G.; Clark, H. C.; Manzer, L. E. *Coord. Chem. Rev.* **1973**, *10*, 335–422. Caldwell, A. N.; Manojlovic-Muir, Lj.; Muir, K. W. *J. Chem. Soc., Dalton Trans.* **1977**, 2265–2269. Hartley, F. R. Platinum. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: New York, 1982; Vol. 6, pp 514–590.

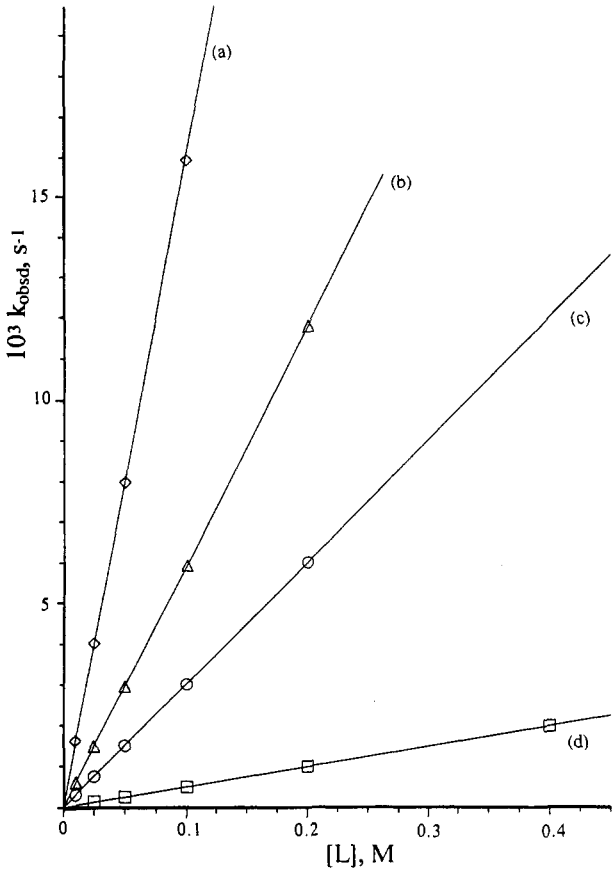

Figure 4. Dependence of the pseudo-first-order rate constants k_{obsd} (s^{-1}) on the concentration of the entering ligand for the reaction of *cis*-[$PtPh_2$-(CO)(Et_2S)] with various reagents at 298.16 K in dichloromethane solution: (a) 4-Me_2Npy; (b) 4-Mepy; (c) py; (d) 2-Mepy.

complexes, using the more sophisticated theoretical Xα method. The dimethyl carbonyl sulfide compound **3** shows a LUMO orbital which is localized between the Pt–C–O atoms, perpendicular to the plane of the molecule. This favorable side of attack by a nucleophilic agent could well explain the bimolecular mechanism exhibited by this compound in its reactions of nucleophilic substitution. Moreover, taking into account that more accurate theoretical calculations could lead to inversions within $\approx$1 eV in the order of the molecular energies, a similar distribution can be considered to be retained also in the dimethyl carbonyl sulfoxide compound **6**, where the energy of the highest UMO, also localized between the Pt–C–O atoms and perpendicular to the plane of the molecule, differs from the LUMO by about 0.7 eV. Likewise, an inversion between the highest UMO, which is essentially the *pz* orbital of the metal atom, and the LUMO orbitals ($\Delta E \approx 0.8$ eV) in the dimethyl bis(sulfoxide) compound **5** could be invoked, and therefore, an associative mechanism for the nucleophilic substitution could be expected. However, the dissociative mechanism proved experimentally for this compound could be mainly determined by the HOMO, which is the d_{z^2} atomic orbital of the platinum atom. This atomic orbital, directed along the *z* axis, is more external with respect to the p_z orbital and the repulsive electronic barrier of the related *lone pair* hinders the approach of the nucleophile to the molecule in the neutral state. The "*electronic barrier*" disappears in the corresponding dichloro bis(sulfoxide) complex **4** in which, as shown in Table III, the HOMO is localized on the plane of the molecule. For the dimethyl disulfide **2** and the dichloro disulfide **1** compounds, the very similar distribution of the HOMO and UMO cannot justify on an electronic basis alone the different mechanistic behavior of these molecules in their reactions of nucleophilic substitution.

As can be seen in Figure 1 the configuration of the electronic potential of compound **3**, which shows large positive values for perpendicular direction to the metal, is certainly favorable to nucleophilic attack. Less favorable but not prohibitive, on the basis of the MEP, seems the attack of a nucleophile to a molecule of **1**, since it shows either positive or negative values of the electrostatic potential for perpendicular direction to the platinum atom. But, there is a positive electrostatic "channel" on the side of the methyl groups of the thioether ligands, which could well be the path pursued by a nucleophilic agent to approach the metal atom. This electrostatic "channel" could not be energetically sufficient to favor the observed associative mechanism. But, simultaneous nucleophilic attack and partial displacement of the outgoing ligand will increase the positive charge around the metal, and therefore, a widening of the positively electrostatic "channel" should favor the associative mechanism with respect to a dissociative mechanism.

The MEP of compound **2** shows that a bimolecular attack of a nucleophile is less likely to occur in the substitution reaction, even if we assume the above concerted mechanism. In fact, (i) the area surrounding the platinum atom with negative values of the electrostatic potential is more extended with respect to that of compound **1**, and (ii) a concerted partial displacement of the outgoing ligand does not give a gain in the energy balance of the reaction, because the increased positive charge on the metal would be neutralized by the electron-donor methyl groups. Therefore, it is reasonable to suppose, according to the experimental findings, that for this compound the complete loss of the leaving group, which produces a three-coordinate intermediate with a large positive area around the platinum atom, is energetically preferred with respect to the addition of a fifth ligand to the substrate and to the formation of a five-coordinate intermediate.

The MEP maps of the sulfoxide compounds **4**–**6** are very similar to those of the sulfide compounds, except for that of compound **5**, in which the negative area around the metal disappears and the electrostatic potential surrounding the platinum atom becomes zero or assumes a small positive value. Therefore, contrary to the MEPs of the compounds **4** and **6**, where the large and positive areas around the metal certainly favor the nucleophilic attack, the map of compound **5** displays an energetic state which makes both mechanisms probable. It is noteworthy that, for sulfoxide compounds, the conformational energy and the related MEP are more affected by the value assumed for the torsional angle about the Pt–S bond, because of the interaction of the metal–sulfoxide orbitals. In Figure 5 are shown the MEPs of compounds **4** and **5**, recalculated for a symmetric conformation where the two oxygen atoms lie on the opposite site with respect to the molecular plane. For this conformation, for which the EHT calculations give a higher value of the energy, the MEP maps are very similar to those of compounds **1** and **2**, and therefore, the same considerations that explained the different kinetic behavior of these compounds apply.

Concluding Remarks

The general trends shown by the MEP maps and some theoretical electronic features of the substrates are in good agreement with the experimental findings. Therefore, if the initial considerations about the potentiality of the MEP analysis are recalled, the good correlation between theoretical results and kinetic behavior in the substitution reactions of these compounds is rather appealing. In principle, the MEP analysis does not give results useful to clearly discriminate among possible reaction pathways. However, this procedure should represent a starting point for a more detailed theoretical analysis when other and more complex factors determining the reaction mechanism are taken into account. Previous kinetic studies have restricted to date the comparison of the pattern of behavior to compounds of the type *cis*-[$PtCl_2L_2$] (classical Werner compounds) and organometallic compounds of the type *cis*-[PtR_2L_2] (R = Me or Ph;

(21) Yang, D. S.; Bancroft, G. M.; Dignard-Bailey, L.; Puddephatt, R. J.; Tse, J. S. *Inorg. Chem.* **1990**, *29*, 2487–2495.

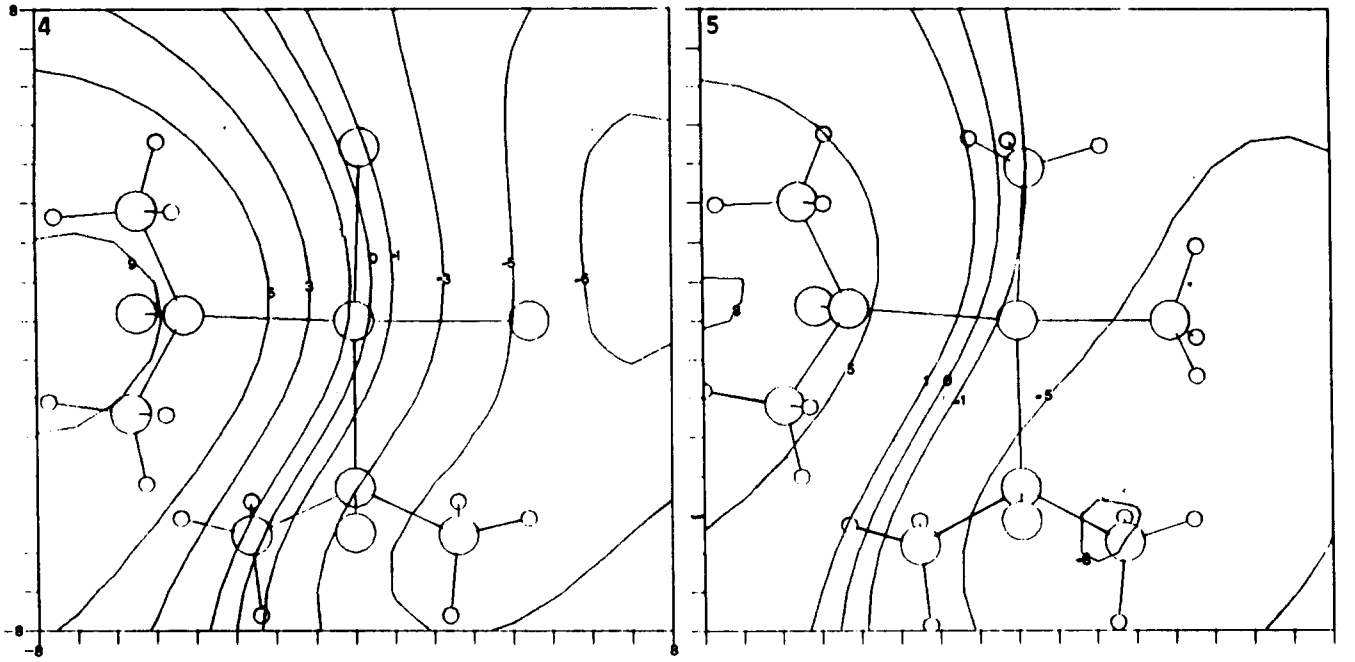

Figure 5. MEP maps of the sulfoxide compounds *cis*-$[PtCl_2(Me_2SO)_2]$ (**4**) and *cis*-$[PtMe_2(Me_2SO)_2]$ (**5**), calculated in the conformation in which the two oxygen atoms lie symmetrically above and below the coordination plane.

L = Me_2S or Me_2SO). The observation of a sharp changeover of reaction pathways, associated with the presence of σ Pt–C bonds, led us to think that the phenomenon was related mainly to ground-state destabilization (lengthening and weakening of the Pt–S bond distance). The most relevant feature of this work is the demonstration that the extent of electron density at the metal center still plays a major role in dictating the choice of the reaction pathway. Dissociation is a combined result of (i) ground-state destabilization (ii) stabilization of the transition state/three-coordinate 14-electron intermediate by way of electron release from the σ-donor ligands to the metal as the outgoing group leaves the coordination sphere, and (iii) increase of electron density at the metal preventing the approach of nucleophiles. The repulsion of the lone pair of the entering nucleophile in the early stages of the reaction and the consequent transfer of charge to the metal is also a way of stabilizing the transition state for dissociative activation. Thus, extensive electron transfer from the ligands to the metal, while decreasing the activation energy for dissociation, also has the effect of creating an electronic barrier to an associative process. When a ligand, such as the carbonyl group in *cis*-$[PtPh_2(CO)(Et_2S)]$, can relieve this excess of electron density, the addition of a fifth ligand and the formation of a five-coordinate transition state again become the preferred pathway for substitution. However, the role of CO in this particular case is not only that of providing an easy associative pathway for substitution but also to suppress the stabilization of a transition state/intermediate of reduced coordination number, as revealed by the absence of any significant concurrent dissociative pathway.

Acknowledgment. We wish to thank MURST and the CNR for financial support.

Supplementary Material Available: Tables SI and SII, giving primary kinetic data (3 pages). Ordering information is given on any current masthead page.