Isomerism of Amides Coordinated to Platinum – X-ray Crystal Structure of *O*-Bonded Acetamide in a Platinum(II) Complex

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O-bonded amide complexes of platinum(II), which are stable in acetone solution and which undergo solvolysis in neat water with a rate constant as slow as $8.7 \cdot 10^{-5}$ s^{-1}, are reported. The structure of a sample compound [Pt(Me$_5$dien)-{*O*-MeC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ has been solved by X-ray diffraction allowing comparison with related *N*-bonded (amide)platinum complexes. Isomerization from *O*-amide to *N*-amidate species takes place instantaneously under basic conditions. Protonation of the amidate species leads to the *N*-bonded amide. *N*-bonded amides, like the *N*-bonded amidates, represent the thermodynamically preferred species due to the higher affinity of platinum for nitrogen donors. In contrast *O*-bonded amides owe their stability to their kinetic inertness, where a high pH is required for deprotonation of the NH$_2$ moiety, the leading step in the isomerization process. In the case of the 2-pyridone complex, the *O*-bonded form is unstable and isomerizes spontaneously to the *N*-bonded form, due to the higher acidity of the protonated pyridine-like nitrogen atom. Two rotamers are present in both the *N*-pyridone and *N*-pyridonate species. Hindered rotation stems from the steric rigidity of both rotating moieties [(Me$_5$dien)Pt and pyridone/pyridonate].

Introduction

Amides of carboxylic acids can be either *O*- or *N*-donor ligands[1]. In the case of *N*-coordination, they can adopt different tautomeric forms {oxo amine [RC(O)NH$_2$] and iminol [RC(OH)NH]}[2].

Changes in the metal center, the R group, or the solvent system can influence the mode of coordination. For complexes of metal ions which are considered to be "hard" Lewis acids, such as [M(NH$_3$)$_5$(amide)$^{3+}$ (M = Co[3], Cr[4], Ru[5], and Rh[6]), the *O*-bonded form was found to be thermodynamically as well as kinetically favored over the *N*-bonded form.

The "softer" platinum(II) species, on the other hand, usually exhibits only a weak affinity for *O*-donor ligands[7] and therefore a thermodynamic preference for *N*-bonded amides is expected. In accordance with this, all platinum compounds characterized by X-ray diffraction analysis[8] contained the amide ligands in the *N*-coordinated tautomeric iminol form. They were prepared by direct reaction with the preformed amide[9] or by hydrolysis of a coordinated nitrile[10][11][12][13][14][15]. However, since these ligands are known to protonate the carbonyl oxygen atom rather than the nitrogen atom[16], there could also be a kinetic preference for *O*-coordination in the case of platinum(II). This possibility has recently been demonstrated in a study showing that acetamide can displace a weakly coordinated water molecule from the [Pt(dien)(OH$_2$)]$^{2+}$ species (dien = diethylenetriamine) acting as an oxygen donor ligand[17][18] in solution. The kinetically preferred *O*-bonded complex can then undergo an intramolecular rearrangement to the thermodynamically more stable *N*-bonded iminol complex[18].

The [Pt(dien){*O*-RC(O)NH$_2$}]$^{2+}$ complexes isomerize to the corresponding *N*-bonded form, as well as undergoing displacement of the *O*-bonded amide by weak nucleophiles such as water. This instability prevented their characterization by X-ray crystallography. In this paper we present the conditions for stabilization of such a species. It was found that using a substituted dien ligand, such as *N,N,N′,N′′,N′′*-pentamethylethylenediamine (Me$_5$dien), *O*-bonded amide complexes, which are infinitely stable in acetone solution and which undergo solvolysis in neat water with a rate constant as low as $8.7 \cdot 10^{-5}$ s^{-1}, can be prepared. The structure of the complex [Pt(Me$_5$dien){*O*-MeC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ (**4b**) has been solved by X-ray diffraction allowing comparison to *N*-bonded platinum amides. Furthermore this investigation has allowed a deeper insight into the mechanism of isomerization from *O*- to the *N*-bonded amides, and other conformational restraints within the coordination sphere.

Results and Discussion

Stereochemistry of the Me$_5$dien Ligand in Solution

The ^{1}H-NMR spectrum in D$_2$O solution of the aqua species [Pt(Me$_5$dien)(H$_2$O)](CF$_3$SO$_3$)$_2$ (**2**) shows three signals for the *N*-Me groups (relative intensities of 3:6:6) and four signals for the protons of the ethylene chains linking

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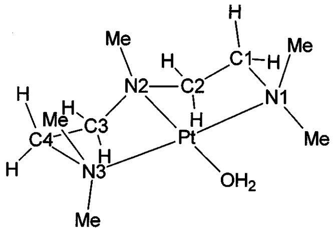
Table 1. ^{1}H-NMR data (δ, downfield from $SiMe_4$; [D_6]acetone solvent) for complexes **1**−**7**[a]

	N(2)Me	Me5dien[b] N(1,3)Me_2	C(1,4)H_2 (ax, eq)	C(2,3)H_2 (ax, eq)	Amide R	$NH_{(1,2)}$	OH
1	3.37	3.28, 3.11	3.82[d]	4.20[d]			
2[c]	3.07	2.94, 2.77	3.51, 3.04	3.68, 2.96			
3a	3.34	3.26, 3.07	3.84, 3.25	4.08, 3.15	1.65		
3b	3.34	3.27, 3.08	3.82, 3.22	4.10, 3.15	2.87		
3c	3.40	3.18, 3.38	3.90, 3.30	4.17, 3.20	8.23(*o*) 7.74(*m*) 7.95(*p*)		
4a	3.24	3.09, 2.86	3.69, 3.21	4.04, 3.12	1.36	9.42, 8.92	
4b	3.26	3.10, 2.91	3.69, 3.21	4.03, 3.13	2.40	9.35, 9.23	
4c	3.31	3.16, 2.95	3.73, 3.28	4.11, 3.19	8.14(*o*) 7.59(*m*) 7.74(*p*)	9.74, 9.70	
5a	3.23	3.07, 2.84	3.71, 3.15	3.93, 3.09	1.37	8.45	11.92
5b	3.26	3.09, 2.86	3.73, 3.17	3.98, 3.12	2.47	8.61	12.27
5c	3.32	3.19, 2.95	3.80, 3.21	4.04, 3.17	8.04(*o*) 7.57(*m*) 7.69(*p*)	9.28	12.60
6	3.31	3.10, 2.80	3.69[d]	4.06[d]	8.08(C^6H) 7.08(C^5H) 8.16(C^4H) 7.86(C^3H)	13.20	
7	3.35	3.07, 2.72	3.85[d]	4.14[d]	9.04(C^6H) 7.27(C^5H) 8.06(C^4H) 7.27(C^3H)		
7′	3.36	2.98, 2.75	3.86[d]	4.04[d]	8.65(C^6H) 7.23(C^5H) 8.03(C^4H) 7.23(C^3H)		

[a] **1** $[Pt(Me_5dien)I]_2Pt_2I_6$, **2** $[Pt(Me_5dien)(H_2O)](CF_3SO_3)_2$, **3** $[Pt(Me_5dien)(N{\equiv}CR)](CF_3SO_3)_2$ [R = *t*Bu (**a**), Me (**b**), and Ph (**c**)], **4** [Pt(Me$_5$dien){*O*-RC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ [R = *t*Bu (**a**), Me (**b**), and Ph (**c**)], **5** [Pt(Me$_5$dien){*N*-RC(OH)NH}](CF$_3$SO$_3$)$_2$ [R = *t*Bu (**a**), Me (**b**), and Ph (**c**)], **6** [Pt(Me$_5$dien){*O*-HNC(O)C^{3}HC^{4}HC^{5}HC^{6}H}(N−C^6)](CF$_3$SO$_3$)$_2$, **7/7′** [Pt(Me$_5$dien){*N*-NC(OH)C^{3}HC^{4}HC^{5}HC^{6}H}-(N−C^6)](CF$_3$SO$_3$)$_2$. − [b] Numbering scheme of the Me$_5$dien ligand: $Me_2N(1)C(1)H_2C(2)H_2N(2)MeC(3)H_2C(4)H_2N(3)Me_2$. − [c] Solvent D_2O. − [d] The signal of the equatorial proton is obscured by overlap.

the central nitrogen atom with the terminal nitrogen atoms (each signal integrating for two protons) (Table 1).

There is a geminal coupling (13 Hz) between the signals at δ = 3.68 and 2.96 and between the signals at δ = 3.51 and 3.04, indicating that the two signals of each couple belong to the same methylene group. From the observation of distinct signals for the two protons of a given methylene group, it is possible to conclude that the two condensed rings have a fixed puckering[19][20]. Two vicinal protons (signals at δ = 3.68 and 3.51) are strongly coupled (ca. 13 Hz), therefore they are both axial (torsion angle of ca. 180°). The other two vicinal protons (δ = 3.04 and 2.96) are weakly coupled (3 Hz) and therefore they are both equatorial (forming a torsion angle of ca. 60°). It is also possible to assign the signals at δ = 3.51 and 3.04 to the methylene group adjacent to the terminal nitrogen atoms (corresponding to C1H$_2$ and C4H$_2$ in Scheme 1) because the axial protons (δ = 3.51) have NOE cross peaks with the central *N*-Me group (δ = 3.07) and two equivalent terminal *N*-Me groups (δ = 2.77). In contrast, the couple of signals at δ = 3.68 and 2.96 can be assigned to the methylene groups adjacent to the central nitrogen atoms (corresponding to C2H$_2$ and C3H$_2$ in Scheme 1) because the axial protons (δ = 3.68) have NOE cross-peaks only with terminal *N*-Me groups (δ = 2.94).



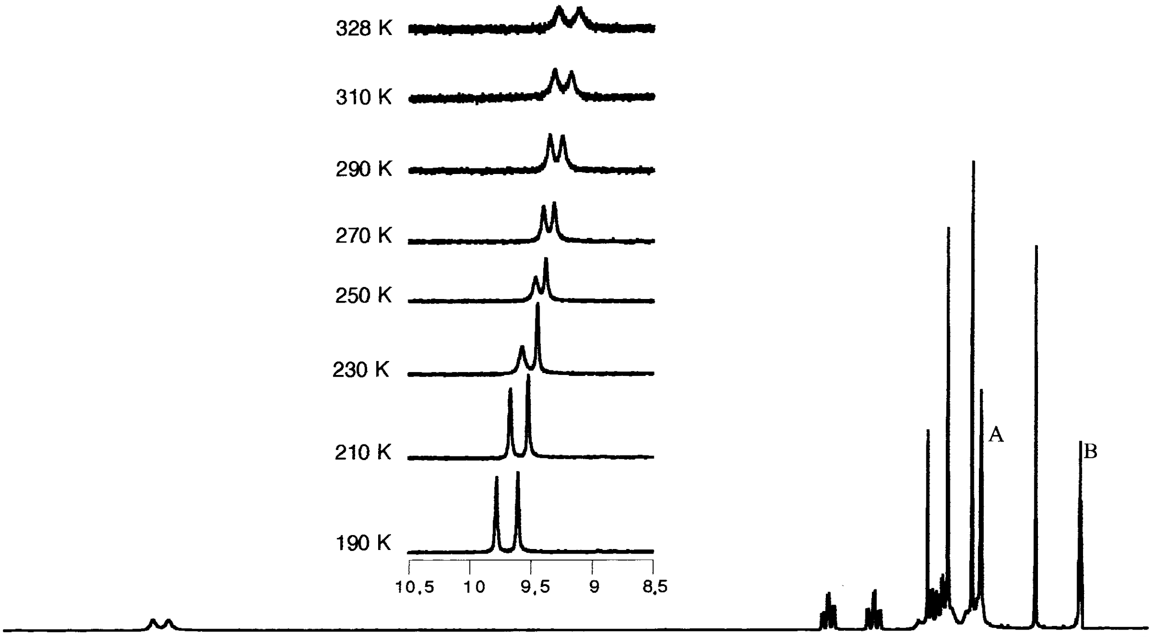
The *N*-Me signal at δ = 2.77, which has NOE cross-peaks with the axial protons of C1H$_2$ and C4H$_2$ methylene groups (δ = 3.51), must belong to the terminal *N*-Me groups which are on the same side of the coordination plane as the central methyl group. The *N*-Me signal at δ = 2.94, having NOE cross-peaks with the axial protons of the C2H$_2$ and C3H$_2$ methylene groups (δ = 3.68), must belong to the terminal *N*-Me groups which are on the opposite side of the coordination plane from the central methyl group.

O-Amide Complexes Formed in the Reaction of the Aqua Species 2 with Free Amide

Reaction of the aqua species **2** with free amide in acetone solution leads to displacement of the coordinated water molecule by the free amide, and formation of the [Pt(Me$_5$dien){*O*-RC(O)NH$_2$}]$^{2+}$ complex [**4**; R = *t*Bu (**a**), Me (**b**), or Ph (**d**)]. The reaction is rather slow (k_{obs} = $3.5 \cdot 10^{-5}$ s^{-1} for 0.1 M acetamide) and requires a slight excess of amide to go to completion. The isolated species, however, can be dissolved in pure water, where they undergo solvolysis at a very slow rate (k_{obs} = $8.7 \cdot 10^{-5}$ s^{-1} for **4b**). It has already been reported that the presence of *N*-substituents can reduce the reactivity of dien complexes by a factor of 300[20][21].

The ^{1}H-NMR spectral features of the Me$_5$dien ligand are very similar to those observed for the aqua species, indicating a similar structure with fixed puckering of the two condensed chelate rings. The *O*-coordination of the amide is deduced from the presence of two close NH$_2$ ^{1}H-NMR signals which are ca. 2 ppm downfield with respect to those of the free amide (in contrast, *N*-coordination is undoubtedly accompanied by a switch to the iminol tautomer with chemical shifts of the NH and OH protons ca. 2 and 4 ppm, respectively, downfield with respect to the NH$_2$ signals of the free ligand). The two NH$_2$ proton signals are rather sharp at low temperature (ca. −80°C) and both undergo broadening and a shift to higher field as the temperature is raised (Figure 1).

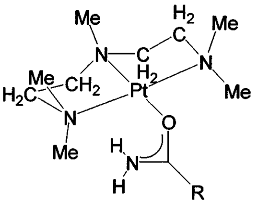
Figure 1. ^{1}H-NMR spectrum (δ, downfield from SiMe$_4$; [D$_6$]acetone as solvent) of [Pt(Me$_5$dien){*O*-MeC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ (**4b**); assignment of resonances as reported in Table 1; A: water moisture, B: [D$_6$]acetone



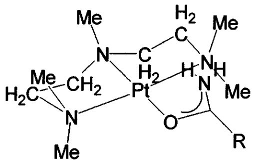
The shift in field and the broadening are more pronounced for one signal. The signal is found more downfield at −80°C and more upfield at +50°C. A possible explanation for this behavior is that at low temperature there is preference for a given isomer and that, as the temperature is raised, a second isomer contributes to the stereochemistry of the complex causing the observed spectral changes. There are two possible causes for isomerism: (i) Restricted rotation of the amide ligand about the Pt−O bond would lead to the formation of two rotamers, differing in the relative position of the amide aminic group and the Me$_5$dien central *N*-Me group with respect to the platinum coordination plane (A and B in Scheme 2); (ii) ligand-coordination isomerism with the Pt atom either *cis* to NH$_2$ or *cis* to R with respect to the C=O double bond (C and D in Scheme 2). Observed similarities among the three complexes with R = *t*Bu (**a**), Me (**b**), or Ph (**d**) suggests that the first hypothesis is more correct.

Conversion of *O*-Bonded to *N*-Bonded Amides by Base Catalysis

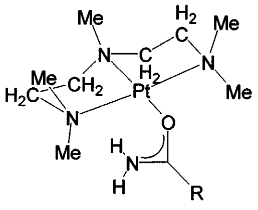
The *O*-bonded amide complexes **4a−c** are stable for weeks in acetone solution under neutral conditions. Treatment with bases, however, leads to instant formation of the corresponding *N*-bonded amidate species. Alkaline bases can be used, but, since they are not soluble in acetone, they must be added in powdered form and with concomitant addition of a few drops of water. Organic nitrogen bases (such as triethylamine) can also be used but displacement of the *O*-bonded amide by the amine can also take place. Treatment of the amidate with an acid (such as triflic acid, CF$_3$SO$_3$H) restores the amide, but to the *N*-bonded form (compounds **5a−c**). The identification of the *N*-bonded amides was facilitated by the preparation of the same species by an alternative route, that is, by hydrolysis of the corresponding nitrile complexes as already reported[11]. The *N*-bonded amides invariably adopt the iminol form with two downfield signals at δ ≈ 12 and 8−9 assigned to the OH and NH protons, respectively. The OH proton generally gives a very broad signal because, being rather acidic (pK_a ≈ 3.7), it exchanges rapidly with water. With time, the



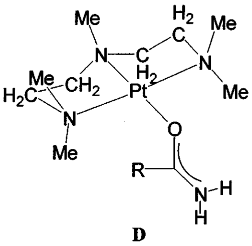
A



B



C



D

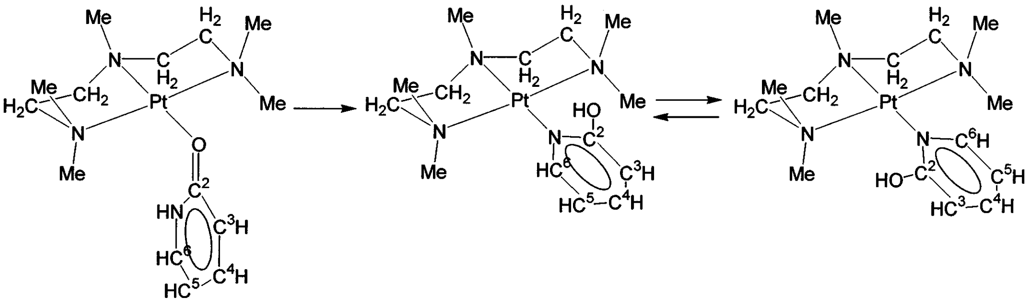
intensities of the OH and H_2O peaks decrease and eventually disappear. However, the intensity of the partially deuterated acetone ([D_5]acetone) peaks increases. Although this type of reaction is not new, in the present case it is exceptionally fast ($k_{obs} = 1.0{\cdot}10^{-4}\ s^{-1}$ at 24°C).

Spontaneous Isomerization of *O*-Bonded to *N*-Bonded 2-Pyridone – Formation of *N*-Bonded Rotamers

The reaction of the aqua species **2** with pyridone leads initially to product **6** which is not stable but isomerizes over time to a new species (**7**) ($k_{obs} = 4.5{\cdot}10^{-5} s^{-1}$ for a pyridone concentration of 2.2 mM at 24°C) (Scheme 3). The NMR spectrum of **6** is in agreement with an *O*-bonded pyridone complex, analogous to the *O*-bonded species (**4a–c**) obtained with other amides. A broad signal at $\delta = 13.2$ was identified as an *N*-bonded proton, the other signals at $\delta = 8.07$, 7.08, 8.16, and 7.86 were easily identified as C^6H, C^5H, C^4H, and C^3H signals, respectively, on the basis of H,H coupling.

Me_5dien ligand. At equilibrium, the two species are present in comparable yields ([**7**]/[**7′**] ≈ 40:60). It is most likely that **7** and **7′** are rotamers resulting from the non-C_2 symmetry of the Me_5dien ligand. This hypothesis has been fully confirmed by an NOE experiment showing that the C^6H signals of the two isomers have cross peaks with different couples of terminal *N*-Me groups: isomer **7′** with the *N*-Me groups which are on the same side of the platinum coordination plane as the central *N*-Me group and isomer **7** with the *N*-Me groups which are on the opposite side of the platinum coordination plane from the central *N*-Me group. It is interesting to note that one of the two rotamers (**7**) is kinetically favored in the isomerization from *O*- to *N*-bonded form, while at equilibrium the two rotamers are nearly equally abundant.

Treatment with base also causes instant isomerization of the *O*-bonded amide complex **6** to the *N*-bonded amidate complex. Furthermore, the amidate species formed first, like the *N*-amide formed first, also isomerizes to a new species (presumably a rotamer). At equilibrium, the ratio of the two rotamers is similar to that observed for the corresponding *N*-amides (**7** and **7′**). Obviously, starting from an equilibrium mixture of **7** and **7′**, treatment with base leads to the corresponding *N*-amidate in the equilibrium isomer composition.



6 **7** **7'**

In the isomerization from **6** to **7**, the signals assigned to C^5H and C^4H remain nearly unchanged ($\Delta\delta \approx 0.2$). In contrast, the signal of the C^6H proton undergoes a downfield shift of ca. 1 ppm ($\delta = 9.04$) and couples to platinum (30 Hz), while the signal of the C^3H proton undergoes an upfield shift of ca. 0.6 ppm ($\delta = 7.26$). The changes in chemical shifts and the coupling with platinum are in agreement with **7** being an *N*-bonded 2-hydroxypyridine complex (2-pyridone and 2-hydroxypyridine are the equivalents of the oxo amine and iminol tautomers of amides).

A peculiar feature of the *N*-bonded pyridone complex **7** is its slow isomerization to a new species (**7′**) (Scheme 3). The rate of isomerization of **7** to **7′** is much slower than the isomerization of **6** to **7**, occurring over several days as compared to a few hours. The new species (**7′**) has spectral features which are also in agreement with an *N*-bonded pyridone (C^6H coupled to platinum, 30 Hz) and a tricoordinate

Insight into the Mechanism of *O*- to *N*-Isomerization of Amides

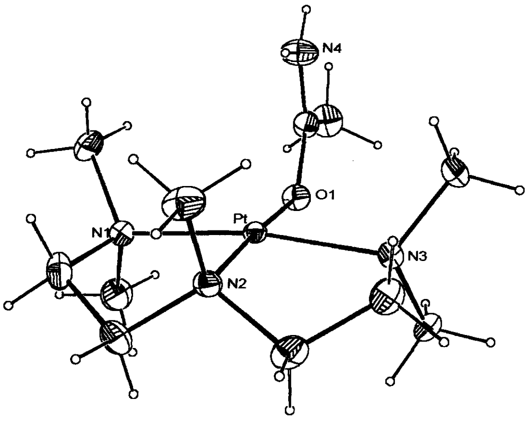
The reason why the isomerization from the *O*- to the *N*-bonded form takes place for the pyridone and not for the other amide complexes under similar experimental conditions (acetone solution, in the absence of added base), deserves further discussion. It has been hypothesized that *O*- to *N*-isomerization of coordinated amides takes place intramolecularly through a transition state in which both N and O atoms of the amide are equally predisposed towards nucleophilic attack on Pt^{II}[18]. It is impossible for the *O*-

bonded amide ligand to adopt a conformation with lone pairs of electrons at the O and N atoms pointing towards the same metal center because of the π-electron delocalization of the nitrogen lone pair of electrons. Therefore the isomerization process ought to take place by deprotonation of the nitrogen atom and conversion of the amide to an amidate species. The latter species can have convergent lone-pairs of electrons at the O and N atoms and can promote a transition state in which both atoms donate a lone pair of electrons to the platinum center. Protonation of the amidate would revert it back to the amide, but in the isomerized *N*-bonded form. On this basis the slow isomerization from *O*- to *N*-coordination of the pyridone, even in the absence of added base, can be explained in terms of the higher acidity of the NH protons in 2-pyridone, as compared to that in acyclic amides.

X-ray Structure Analysis of the (*O*-Acetamide)platinum Complex 4b

An X-ray Structure analysis of complex **4b**, for which the *O*-coordination of the amide had already been established by NMR experiments, has been carried out in order to compare structural features of the amide functionality in the *O*- and *N*-coordinated linkage isomerism. An ORTEP drawing of **4b** is shown in Figure 2. Selected bond lengths and angles are given in Table 2. The crystals of **4b** consist of the complex cation $[Pt(Me_5dien)\{O\text{-}MeC(O)NH_2\}]^{2+}$ and triflate anions in a 1:2 molar ratio. The platinum atom has the usual square-planar ligand coordination sphere in which the three nitrogen atoms from Me_5dien and the oxygen atom from the acetamide act as donors.

Figure 2. ORTEP drawing of $[Pt(Me_5dien)\{O\text{-}MeC(O)NH_2\}](CF_3SO_3)_2$ (**4b**) with the labelling scheme; the ellipsoids enclose 30% probability



The Pt−N(1) and Pt−N(3) bonds (terminal aminic groups) have similar lengths [2.056(5) and 2.065(5) Å, respectively] and both are significantly longer than the Pt−N(2) bond [2.007(5) Å] (central aminic group). The N(1)−Pt−N(2) and N(2)−Pt−N(3) angles of the two condensed chelate rings are significantly smaller than 90° [86.3(2) and 86.5(2)°, respectively]. In contrast, the N(1)−Pt−O(1) and N(3)−Pt−O(1) angles are significantly larger than 90° [93.0(2) and 93.6(2)°, respectively]. The strain within the tridentate ligand appears to be responsible for the observed deviation from planarity of the (Me_5dien)Pt moiety, where the platinum atom is displaced by 0.140 Å above the plane of the three nitrogen donors)[23].

Table 2. Selected bond lengths [Å] and angles [°] of $[Pt(Me_5dien)\{O\text{-}MeC(O)NH_2\}](CF_3SO_3)_2$; standard deviations are in parentheses

Pt−N(1)	2.056(5)	N(3)−C(4)	1.504(8)
Pt−N(2)	2.007(5)	N(3)−C(8)	1.487(8)
Pt−N(3)	2.065(5)	N(3)−C(9)	1.485(7)
Pt−O(1)	2.038(4)	O(1)−C(10)	1.262(7)
N(1)−C(1)	1.509(10)	C(1)−C(2)	1.515(12)
N(1)−C(5)	1.493(10)	C(3)−C(4)	1.498(10)
N(1)−C(6)	1.488(9)	C(10)−N(4)	1.303(9)
N(2)−C(2)	1.496(9)	C(10)−C(11)	1.498(9)
N(2)−C(3)	1.499(8)	N(4)−H(a)	0.78(9)
N(2)−C(7)	1.482(8)	N(4)−H(b)	0.96(9)
N(1)−Pt−N(2)	86.3(2)	N(2)−C(3)−C(4)	108.0(5)
N(1)−Pt−N(3)	169.7(2)	N(3)−C(4)−C(3)	110.8(5)
N(1)−Pt−O(1)	93.0(2)	O(1)−C(10)−N(4)	123.4(6)
N(2)−Pt−N(3)	86.5(2)	O(1)−C(10)−C(11)	117.4(6)
N(2)−Pt−O(1)	175.4(2)	C(1)−N(1)−C(5)	108.0(6)
N(3)−Pt−O(1)	93.6(2)	C(1)−N(1)−C(6)	109.7(6)
Pt−N(1)−C(1)	107.2(4)	C(5)−N(1)−C(6)	108.4(6)
Pt−N(1)−C(5)	108.8(4)	C(2)−N(2)−C(3)	112.7(5)
Pt−N(1)−C(6)	114.7(4)	C(2)−N(2)−C(7)	110.6(6)
Pt−N(2)−C(2)	104.7(4)	C(3)−N(2)−C(7)	111.0(6)
Pt−N(2)−C(3)	104.9(4)	C(4)−N(3)−C(8)	108.7(5)
Pt−N(2)−C(7)	113.6(4)	C(4)−N(3)−C(9)	110.3(5)
Pt−N(3)−C(4)	106.1(4)	C(8)−N(3)−C(9)	108.0(5)
Pt−N(3)−C(8)	107.3(4)	N(4)−C(10)−C(11)	119.2(6)
Pt−N(3)−C(9)	116.2(4)	C(10)−N(4)−H(a)	119(7)
Pt−O(1)−C(10)	127.3(4)	C(10)−N(4)−H(b)	116(6)
N(1)−C(1)−C(2)	109.9(6)	H(a)−N(4)−H(b)	125(9)
N(2)−C(2)−C(1)	108.0(6)		

The Pt−O bond length [2.038(4) Å] is in agreement with the values of Pt−O lengths previously reported for *N,O*-2-pyridonate complexes $[Pt_2(en)_2(C_5H_4NO)_2]_2^{4+}$ [2.049(6) Å][24] and $[Pt_2(NH_3)_4(C_5H_4NO)_2]^{2+}$ [2.024(5) Å] (where C_5H_4NO = 2-pyridonate)[25].

The acetamide molecule is strictly planar, with deviations of the heavy atoms from the least-square plane of ca. 0.004(6) Å, and orthogonal to the coordination plane where the dihedral angle between the planes is 89.4(3)°. The C−O and C−N bond lengths within the acetamide ligand [1.262(7) and 1.303(9) Å, respectively] are very similar to those previously found for acetamide *O*-coordinated to nickel [1.248(3) and 1.311(4) Å, respectively][26] and for free amides [1.23(1) and 1.32(1) Å, respectively][27] and indicate an extensive π-bond delocalization over the O$\cdots$C$\cdots$N functionality. Compared to the *N*-coordinated (acetamide)platinum species, the trend in C−O and C−N bond lengths is reversed [1.321(14) and 1.275(13) Å, for C−O and C−N, respectively][13]. This is in agreement with the different tautomerism of the acetamide in the two cases (oxo amine in the *O*-bonded and iminol in the *N*-bonded forms). The platinum−donor distances are also comparable to *O*- and *N*-bonded acetamide (within 0.01 Å).

The NH_2 group of the amide ligand is *cis* to the platinum center with respect to the C=O double bond and comes close to it. The intramolecular distance between the platinum atom and one proton of the amide [H(a)] is 2.86(9) Å (as compared to the sum of the van der Waals radii for Pt and H of 2.9−3.2 Å)[28] and the Pt···H(a)−N(4) angle is 114(7)°. These data indicate the existence of an attractive Pt···H(a) interaction. Similarly, an interaction between the hydroxy group and the platinum atom was observed in the *N*-bonded acetamide [Pt···HO = 2.56(2)Å, Pt···H−O = 124(8)°] and was believed to be responsible for the stabilization of the isomer with the OH group, instead of the isomer with the Me group *cis* to the Pt center across the C=N double bond. The same conclusion can be drawn in the present case, although the Pt···HN interaction appears to be slightly weaker than the Pt···HO interaction.

The N(2)−Pt−O axis is slightly bent [175.4(2)°] in the same direction as the N(1)−Pt−N(3) axis [169.6(2)°] and, as a consequence, the coordination sphere of the platinum center assumes a pyramidal distortion, with the Pt atom displaced by 0.104(1) Å above the average plane of the donor atoms. This distortion contrasts with the tetrahedral distortion observed in the related [Pt(Me$_5$dien)I]$^+$ complex[29].

The triflate anions are kept in the vicinity of the metal center by a hydrogen bond between a triflate oxygen atom and the NH$_2$ group of the amide. The hydrogen bonds have geometrical parameters: O(2)−N(4) 2.837(9) Å, O(2)−H(b) 2.02(9) Å, O(2)−H(b)−N(4) 175.9(9)°, and O(5)−N(4) 3.050(11) Å, O(5)−H(a) 2.35(9) Å, O(5)−H(a)−N(4) 149(9)°[22].

Conclusions

In spite of the higher affinity of platinum(II) for *N*- over *O*-donor ligands, suitable platinum substrates react preferentially with the oxygen terminus to give the *O*-bonded amide complexes. Although the *O*-bonded species are very labile, since the amide can be displaced by water, they are indefinitely stable in acetone solution under neutral conditions. In contrast, isomerization from *O*- to *N*-bonded species takes place instantly under basic conditions. Therefore, the deprotonation of the aminic group ($pK_a > 11$) is accompanied by the shift of the metal center from the *O*- to the *N*-atom, leading to the formation of *N*-bonded amidate species. The main factor leading to the isomerization is the higher affinity of platinum to the nitrogen over the oxygen donor atom.

Protonation of the amidate species under acidic conditions leads to the *N*-bonded amide. The *N*-bonded amides, like the *N*-bonded amidates, represent the thermodynamically preferred species due to the higher affinity of platinum to nitrogen donors. In contrast, *O*-bonded amides owe their stability to their kinetic inertness, where a high pH is required for deprotonation of the NH$_2$ functionality. In the case of the pyridone complex, the *O*-bonded form is unstable and isomerizes spontaneously to the *N*-bonded form. The isomerization from the *O*- to the *N*-bonded species can take place in the absence of added base because of the higher acidity of the protonated pyridine-like nitrogen atom.

Differently to dien, Me$_5$dien adopts a fixed puckering of the two condensed chelate rings. Due to the rigidity of the puckered ring, the methyl groups at the terminal nitrogen atoms are held in fixed positions and strongly hinder the rotation of the amide. The steric hindrance is expected to be particularly severe in the case of cyclic pyridone. In this case, we have convincing evidences for the presence of two rotamers in both the *N*-amide and the *N*-amidate species. Hindered rotation stems from the steric rigidity of both rotating fragments, namely the (Me$_5$dien)Pt moiety and the pyridone. Slow rotation (on the NMR time scale) of aryl[22], pyrimidine, and purine rings in (Me$_5$dien)Pd^{2+} complexes has already been reported[20]. This, however, is the first case that such a rate has been measured and found to be exceptionally low.

Comparison of the X-ray structure analysis of *O*- and *N*-coordinated (acetamide)platinum complexes has confirmed that because of the change in the ligand tautomerism (oxo amine and iminol for *O*- and *N*-bonded amides, respectively), the two isomeric amide functionalities are nearly superimposable.

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Experimental Section

Starting Materials: Commercial reagent-grade chemicals were used without further purification.

Preparation of the Complexes: [Pt(Me$_5$dien)I]$_2$(Pt$_2$I$_6$) (**1**) was prepared by direct reaction of K$_2$[PtI$_4$] with free amine. In a typical experiment K$_2$PtCl$_4$ (0.5 g, 1.2 mmol) was dissolved in water (5 ml) and treated with excess KI (0.82 g, 4.9 mmol). After 5 min of stirring at 50°C, a stoichiometric amount of Me$_5$dien (0.207 g, 1.2 mmol) was added and the reaction mixture was kept stirring at 50°C for 1 h. The yellow-green precipitate which formed was separated, washed with water, and dried in dry air. Yield: 0.55 g, 67%. − C$_{18}$H$_{46}$I$_8$N$_6$Pt$_4$ (**1**; 2141.5): calcd. C 10.1, H 2.2, N 3.9; found C 10.0, H 2.2, N 3.9.

[Pt(Me$_5$dien)(H$_2$O)](CF$_3$SO$_3$)$_2$ (**2**) was prepared from [Pt(Me$_5$dien)I]$_2$(Pt$_2$I$_6$) (**1**) (0.3 g, 0.14 mmol), suspended in water (20 ml) and treated with silver triflate (0.15 g, 0.58 mmol). The reaction mixture was kept stirring for about 16 h at room temperature in the dark. The solution was then filtered through Celite and concentrated to dryness. The oily residue was triturated with diethyl ether to give a white hygroscopic solid. Yield: 0.150 g, 40%. − C$_{11}$H$_{27}$F$_6$N$_3$O$_8$PtS$_2$ (**2**; 702.1): calcd. C 18.8, H 3.9, N 6.0; found C 18.8, H 3.8, N 5.8.

The complexes [Pt(Me$_5$dien)(N≡CR)](CF$_3$SO$_3$)$_2$ (**3**) were prepared by reaction of the aqua species [Pt(Me$_5$dien)(H$_2$O)](CF$_3$SO$_3$)$_2$ (**2**) with free nitrile. In a typical experiment, [Pt(Me$_5$dien)(H$_2$O)](CF$_3$SO$_3$)$_2$ (**2**) was dissolved in the minimum amount of the appropriate nitrile [N≡CR, R = *t*Bu (**a**), Me (**b**), and Ph (**c**)] (ca. 1 mmol of complex in about 10 ml of nitrile) and then kept stirring for 1 h at room temperature. In the case of *tert*-butyl cyanide, the complex **3a** precipitated from the reaction solution and was recovered by filtration of the mother liquor. In the case of acetonitrile, the complex **3b** was recovered after evaporation of the solvent and trituration of the oily residue with diethyl ether. Finally, in the case of benzonitrile, an excess of *n*-hexane was added

Table 3. Selected crystallographic data of [Pt(Me$_5$dien){*O*-MeC(O)NH$_2$}](CF$_3$SO$_3$)$_2$

Empirical formula	$C_{13}H_{28}F_6N_4O_7PtS_2$	$d_{calcd.}$ [Mg m^{-3}]	1.940
Formula mass	725.58	μ(Cu-K_α), [cm^{-1}]	129.17
Space group	*P*21/*n*	Crystal size [mm]	0.4 × 0.15 × 0.15
a [Å]	11.631(2)	θ range [°] for data collection	$2 < 2\Theta < 140$
b [Å]	12.4217(9)	Independent reflections	4705 [$R_{int} = 0.0163$]
c [Å]	17.314(2)	Observed reflections [$F > 4\sigma(F)$] used for the final refinement	4690
β [°]	96.002(9)	Absorption correction	DIFABS
V [Å^3]	2487.8(4)	Refinement method	Full-matrix least-squares on F^2
Z	4	*R*1[a]	0.0378
Temperature [°C]	25	*wR*2[a]	0.0985
F(000)	1416	Parameters refined	311
Radiation (λ [Å])	1.5418		

[a] $R1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. – [b] $wR2 = [\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]]^{1/2}$; $w = 1/[\sigma^2(F_o^2) + (0.0631 \times P)^2 + 21.74 \times P]$ where $P = [\mathrm{Max}(F_o^2,0) + 2 \times F_c^2]/3$.

to the solution and the mixture kept in the refrigerator for 1 d. The sticky precipitate which formed was washed three times with *n*-hexane and then treated with diethyl ether to give a solid product **3c**. In all cases the yields were above 75%. – $C_{16}H_{32}F_6N_4O_6PtS_2$ (**3a**; 749.1): calcd. C 25.6, H 4.3, N 7.5; found C 25.4, H 4.4, N 7.4. – $C_{13}H_{26}F_6N_4O_6PtS_2$ (**3b**; 707.1): calcd. C 22.1, H 3.7, N 7.9; found C 21.7, H 3.6, N 7.7. – $C_{18}H_{28}F_6N_4O_6PtS_2$ (**3c**; 769.1): calcd. C 28.1, H 3.7, N 7.3; found C 27.8, H 3.5, N 6.9.

The *O*-bonded amide complexes [Pt(Me$_5$dien){*O*-RC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ (**4**) [R = *t*Bu (**a**), Me (**b**), and Ph (**c**)] were prepared by reaction of the aqua species [Pt(Me$_5$dien)(H$_2$O)](CF$_3$SO$_3$)$_2$ (**2**) with the free amide according to a slight modification of the method of Woon and Fairlie[18]. In a typical experiment, compound **2** (0.07 g, 0.1 mmol) was dissolved in acetone (10 ml), treated with the free amide [RC(O)NH$_2$, R = *t*Bu (**a**), Me (**b**), and Ph (**c**)] (0.15 mmol) and then kept stirring for 16 h at room temperature. Addition of a large excess of diethyl ether induced complete precipitation of the compound. The white precipitate was collected and dried in a vacuum desiccator in the presence of KOH pellets as the drying agent, with the yields always above 90%. In the case of acetamide, suitable crystals for X-ray diffraction were obtained by slow crystallization from an acetone solution layered under diethyl ether. – $C_{16}H_{34}F_6N_4O_7PtS_2$ (**4a**·H$_2$O; 767.1): calcd. C 25.0, H 4.5, N 7.3; found C 24.9, H 4.6, N 7.1. – $C_{13}H_{28}F_6N_4O_7PtS_2$ (**4b**·H$_2$O; 725.1): calcd. C 21.5, H 3.9, N 7.7; found C 21.4, H 3.9, N 7.7. – $C_{18}H_{30}F_6N_4O_7PtS_2$ (**4c**·H$_2$O; 787.1): calcd. C 27.4, H 3.8, N 7.1; found C 26.8, H 3.9, N 7.1.

The *N*-bonded amide complexes [Pt(Me$_5$dien){*N*-RC(OH)NH}](CF$_3$SO$_3$)$_2$ (**5**) [R = *t*Bu (**a**), Me (**b**), and Ph (**c**)] were prepared either by hydrolysis of the corresponding nitriles (procedure 1) or by isomerization of the *O*-bonded amides (procedure 2). – Procedure 1: In a typical experiment, the nitrile complex [Pt(Me$_5$dien)(N≡CR)] (CF$_3$SO$_3$)$_2$ (0.1 mmol), dissolved in water (10 ml), was treated with a slight excess of KOH (0.12 mmol in 10 ml of water) with stirring, in an ice bath. After 1–2 h reaction time, the resulting solution was brought to pH = 2–3 with triflic acid, the solvent was evaporated, and the sticky residue crystallized from acetone/diethyl ether. The products **5a–c** are hygroscopic and must be stored under anhydrous conditions. Yields 70%. – Procedure 2: In a typical experiment, the *O*-bonded complex [Pt(Me$_5$dien){*O*-RC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ (**4**) (0.1 mmol), was dissolved in acetone (25 ml) and treated with powdered KOH (0.7 mmol). A few drops of water were added to the reaction mixture, which was kept stirring for about 5 min. The solution was filtered, acidified with triflic acid, and then treated with diethyl ether to allow precipitation of a white product which was recrystallized from acetone/diethyl ether. Yields 70%. – $C_{17}H_{34}F_9KN_4O_{10}PtS_3$ (**5a**·KCF$_3$SO$_3$·H$_2$O; 955.1): calcd. C 21.4, H 3.6, N 5.8; found C 21.3, H 3.8, N 5.7. – $C_{27}H_{56}F_{15}KN_8O_{17}Pt_2S_5$ (**5b**·KCF$_3$SO$_3$·2 H$_2$O; 1638.1): calcd. C 19.8, H 3.4, N 6.8; found C 19.5, H 3.5, N 6.6. – $C_{19}H_{30}F_9KN_4O_{10}PtS_3$ (**5c**·KCF$_3$SO$_3$·H$_2$O; 975.0): calcd. C 23.4, H 3.1, N 5.7; found C 23.3, H 3.5, N 5.6.

The reaction of the acqua species **2** with pyridone leading to a first reaction product (*O*-coordinated pyridone; **6**) which is not stable but isomerizes with time to a new species (*N*-coordinated pyridone; **7**) which, in turn, gives rise to formation of an equilibrium mixture of two rotamers (**7** and **7′**) was performed in the NMR tube and no attempt to isolate isomerically pure species was made.

Physical Measurements: IR spectra in the range 4000–400 cm^{-1} were recorded as KBr pellets; spectra in the range 400–200 cm^{-1} were recorded as polythene pellets with Perkin Elmer 283 and FT 1600 spectrophotometers. ^{1}H-NMR spectra were obtained with a Bruker AM 300 spectrometer and are collected in Table 1. Rate constants were calculated from plots of $\ln(C_t - C_{inf.})$ against time where C_t and $C_{inf.}$ are concentrations at time *t* and after at least six half-lives, respectively.

X-ray Crystallographic Study[30]: Colorless crystals of [Pt(Me$_5$dien){*O*-RC(O)NH$_2$}](CF$_3$SO$_3$)$_2$ (**4b**) were obtained from acetone/diethyl ether solution. X-ray data were collected with an Enraf-Nonius CAD4 single-crystal diffractometer by using graphite-filtered Cu-K_α radiation (λ = 1.5418 Å). The unit-cell dimensions were refined by a least-squares algorithm using 25 automatically centered reflections. A total of 5101 reflections were collected in the range $-14 \le h \le 14$, $0 \le k \le 15$, $0 \le l \le 21$; 4705 independent reflections. Four reflections were monitored during data collection, no decay was observed. Crystallographic data are summarized in Table 3. The full data set was corrected for Lorentz and polarization effects. A correction for absorption effects was applied using the DIFABS package[31] at the isotropic stage of refinement.

The structure was solved using Patterson and Fourier techniques, in the *P*21/*n* space group. The model was refined by full-matrix least-squares methods. Anisotropic thermal parameters were applied for all non-hydrogen atoms. The NH$_2$ hydrogen atoms of the amide were found in the final Fourier difference map, the other hydrogen atoms were placed at their geometrically calculated positions and included in the full-matrix least-square cycles with isotropic thermal parameters (U) tied at 1.2 times the values of U of the relative carbon or nitrogen atoms.

All calculations were carried out with Vax 11/750 and AST Pentium 100 MHz computers using the SHELX-86[32], SHELXL-93[33], and PARST97 packages[34].

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[1] H. Sigel, R. B. Martin, *Chem. Rev.* **1982**, *82*, 385.

[2] D. P. Fairlie, H. Taube, *Inorg. Chem.* **1985**, *24*, 3199.

[3] R. L. Angel, D. P. Fairlie, W. G. Jackson, *Inorg. Chem.* **1990**, *29*, 20.

[4] N. J. Curtis, G. A. Lawrence, A. M. Sargeson, *Aust. J. Chem.* **1983**, *36*, 1495.

[5] D. P. Fairlie, Y. Ilan, H. Taube, *Inorg. Chem.* **1997**, *38*, 1029.

[6] N. J. Curtis, N. E. Dixon, A. M. Sargeson, *J. Am. Chem. Soc.* **1983**, *105*, 5347.

[7] F. R. Hartley, *The Chemistry of Platinum and Palladium*, Applied Sciences Publishers, London, New York, **1973**.

[8] Our considerations will be restricted to monodentate amides and will not include bridging amide complexes for which the reader may refer to the following papers: J. K. Barton, H. N. Rabinowitz, D. J. Szulda, S. J. Lippard, *J. Am. Chem. Soc.* **1977**, *99*, 2827. − T. V. O'Halloran, P. K. Masharak, I. D. Williams, M. M. Roberts, S. J. Lippard, *Inorg. Chem.* **1987**, *26*, 1261. − F. D. Rochon, P. C. Kong, R. Melanson, *Inorg. Chem.* **1990**, *29*, 1352. B. Lippert, *Prog. Inorg. Chem.* **1989**, *37*, 1.

[9] D. B. Brown, M. B. Robin, R. D. Burbank, *J. Am. Chem. Soc.* **1968**, *90*, 5621. − D. B. Brown, R. D. Burbank, M. B. Robin, *J. Am. Chem. Soc.* **1969**, *91*, 2895.

[10] R. Cini, F. P. Fanizzi, F. P. Intini, G. Natile, *J. Am. Chem. Soc.* **1991**, *113*, 7805.

[11] R. Cini, F. P. Fanizzi, F. P. Intini, G. Natile, *J. Am. Chem. Soc.* **1993**, *115*, 5123.

[12] R. Cini, F. P. Intini, G. Natile, C. Pacifico, *J. Chem. Soc., Dalton Trans.* **1994**, 3753.

[13] R. Cini, F. P. Fanizzi, F. P. Intini, G. Natile, C. Pacifico, *Inorg. Chim. Acta* **1996**, *251*, 111.

[14] R. Cini, F. P. Fanizzi, F. P. Intini, C. Pacifico, G. Natile, *Inorg. Chim. Acta* **1997**, *264*, 279.

[15] A. Erxleben, I. Mutikainen, B. Lippert, *J. Chem. Soc., Dalton Trans.* **1994**, 3667.

[16] J. Zabicky, *The Chemistry of Amides*, J. Wiley-Interscience, New York, **1970**, chapter 1, p. 1.

[17] J. S. Kerrison, P. J. Sadler, *J. Chem. Soc., Chem. Commun.* **1981**, 61.

[18] T. C. Woon, D. P. Fairlie, *Inorg. Chem.* **1992**, *31*, 4069.

[19] T. P. Pitner, R. B. Martin, *J. Am. Chem. Soc.* **1971**, *93*, 4400.

[20] S.-H. Kim, R. B. Martin, *Inorg. Chim. Acta* **1984**, *91*, 11.

[21] W. H. Baddley, F. Basolo, *J. Am. Chem. Soc.* **1966**, *88*, 2944.

[22] B. A. Markies, P. Wijkens, J. Boersma, H. Kooijman, N. Veldman, A. L. Spak, G. van Koten, *Organometallics* **1994**, *13*, 3244.

[23] B. A. Markies, P. Wijkens, H. Kooijman, A. L. Spek, J. Boersma, G. van Koten, *J. Chem. Soc. Chem. Commun.* **1992**, 1420.

[24] L. S. Hollis, S. J. Lippard, *Inorg. Chem.* **1983**, *22*, 2600.

[25] L. S. Hollis, S. J. Lippard, *J. Am. Chem. Soc.* **1983**, *105*, 3494.

[26] M. E. Stone, B. E. Robertson, E. Stanley, *J. Chem. Soc. A* **1971**, 3632.

[27] F. H. Allen, O. Kennard, D. G. Watson, L. Brammer, G. Orpen, R. Taylor, *J. Chem. Soc., Perkin Trans. 2* **1987**, S1.

[28] A. Bondi, *J. Phys. Chem.* **1964**, *68*, 441.

[29] F. P. Intini, C. Pacifico, G. Natile, unpublished results.

[30] Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Center as supplementary publication no. CCDC-101247. Copies of the data may be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: (internat.) + 44(0)1223/336033; e-mail: deposit@ccdc.cam.ac.uk].

[31] N. Walker, D. Stuart, "DIFABS", *Acta Crystallogr., Sect. A.* **1983**, *39*, 158.

[32] G. M. Sheldrick, *SHELXS-86*, University of Göttingen, **1986**.

[33] G. M. Sheldrick, *SHELXL-93*, University of Göttingen, **1993**.

[34] M. Nardelli, *PARST 97*, University of Parma, **1996**.

[98083]