Fluxional Interconversion of Divalent Palladium Complexes Having NSNSN Ligands between Flexible SNS and Rigid NNN-Coordinated Structures

Yumi Kawada, Yasutaka Kataoka, Yasuyuki Ura*

Department of Chemistry, Faculty of Science, Nara Women’s University, Kitauoyanishi-machi, Nara 630-8506, Japan
E-mail: ura@cc.nara-wu.ac.jp

Table of Contents Entry

NSNSN-palladium complexes were found to have flexible SNS and rigid NNN coordination modes, and the equilibrium could be modulated by temperature and steric and electronic factors of the ligands.
Fluxional Interconversion of Divalent Palladium Complexes Having NSNSN Ligands between Flexible SNS and Rigid NNN-Coordinated Structures

Yumi Kawada, Yasutaka Kataoka, Yasuyuki Ura*

Department of Chemistry, Faculty of Science, Nara Women’s University, Kitaouyanishi-machi, Nara 630-8506, Japan
E-mail: ura@cc.nara-wu.ac.jp

Abstract
Mono- and dicationic divalent palladium complexes having 2,6-bis(N-heteroaryl sulfanyl)methyl)pyridine ligands (NSNSN ligands) were synthesized and characterized. The NSNSN ligands were fixed in a rac-SNS tridentate coordination mode in the solid state, while the equilibria among meso-SNS, rac-SNS, and NNN isomers were observed in solution. The equilibrium between the SNS and NNN isomers could be modulated by temperature, as well as by the steric and electronic factors of the NSNSN and monodentate ligands. Lowering the temperature tended to make NNN isomers more predominant compared with SNS isomers. On the other hand, the steric demand between the ligands in the complexes shifted the equilibrium from NNN to SNS isomers. Introduction of pyridyl groups instead of pyrimidyl groups as N-heteroarenes also shifted the equilibrium to SNS isomers. DFT calculation indicated rapid ring inversion of the metallacycle moieties and relatively slow S-inversion in the SNS isomers, a result that was in good agreement with the experimentally observed dynamic behaviors. Both the experimental and theoretical results revealed that the SNS isomers had flexible structures in solution, whereas the NNN isomers were rigid and less dynamic. The mechanistic pathways for interconversion between SNS and NNN isomers were also calculated. Such calculations indicated that a pathway featuring a relatively unstable, distorted α-SNN intermediate was plausible. The intermediate had a N-heteroarene on the coordinated sulfur atom at an axial position.
Introduction

Transition-metal complexes with hemilabile hybrid ligands contain two or more different types of functionalities capable of coordinating to metals. These complexes are attractive because they perform fluxional functions such as opening and occupying coordination sites, and therefore develop inherent reactivities and catalytic activities.\(^1\)\(-\)\(^7\) Palladium complexes that have bidentate or tridentate hybrid ligands containing nitrogen and sulfur atoms (SN, SNS or NSN ligands) have been well studied. Such work has focused on the behaviors of the complexes\(^8\)\(-\)\(^17\) as well as the influences of the ligand hemilability on fundamental reactions, such as insertion of unsaturated compounds into Pd-C bonds,\(^17\)\(\)\(^19\)\(-\)\(^24\) attack of nitrogen nucleophiles to \(\eta^3\)-allyl complexes,\(^25\)\(-\)\(^28\) and catalytic reactions such as the Mizoroki-Heck reaction\(^29\),\(^30\) and allylic substitution.\(^31\) Structurally distinctive Pd-SNS complexes with macrocyclic architectures,\(^32\)\(-\)\(^35\) dendrimer,\(^36\),\(^37\) or carborane\(^38\)-incorporated Pd-SNS complexes, as well as the Pd-SN complexes with cysteine-derived ligands\(^39\) have been also reported. On the other hand, transition-metal complexes having available, free basic moieties adjacent to the metal center are also intriguing. In these systems, the metal atom can collaborate with the basic moieties to show reactivities such as cooperative proton transfer,\(^40\)\(-\)\(^42\) base-assisted O-H bond activation,\(^43\)\(-\)\(^46\) and intramolecular C(sp\(^3\))-H bond activation.\(^47\) In this context, we focused on palladium complexes bearing 2,6-bis(N-heteroarylsulfanyl)methyl)pyridine ligands (NSNSN ligands), which have pyrimidyl or pyridyl groups as \(N\)-heteroarenes at both terminals. These hybrid ligands are readily accessible, and the complexes are expected to show potentially unique reactivity derived from the synergy of the hemilability and serving free basic nitrogen moieties adjacent to palladium. Here, we report the synthesis, characterization, and behavior of the divalent palladium complexes having the NSNSN ligands. During our investigation, we found the following: (i) the complexes can have both flexible SNS and rigid NNN coordination modes; (ii) they are in equilibrium in solution; and (iii) their coordination modes can be modulated by temperature as well as by the steric and electronic factors of the NSNSN and monodentate ligands. Their static and dynamic behaviors in solution were examined by variable temperature \(^1\)H NMR measurements. DFT calculations were also performed to determine the isomerization pathways between individual SNS isomers, as well as those between SNS and NNN isomers.

Results and discussion

Synthesis of complexes 1–4 and solid state structures of 2 and 4

The NSNSN multidentate ligands (Fig. 1) were prepared from 2,6-bis(chloromethyl)pyridine and the corresponding aryl thiols.\(^48\) Complexes 1–3 were synthesized in high yields (77–94\%) by the reaction of [PdCl\(_2\)(MeCN)\(_2\)] with 1 equiv. each of the corresponding NSNSN ligand and AgOTf in CH\(_3\)CN at room temperature (Scheme 1).
In the case of complex 4, [PdCl₂(MeCN)₂] was first reacted with 1 equiv. of PPh₃ in CH₂Cl₂ at room temperature and then 1 equiv. of PSMePy and 2 equiv. of AgOTf were added (Scheme 2).

The solid-state structures of complexes 2 and 4 were confirmed by single crystal X-ray crystallography. In the structure of 2, PySMePy coordinates to palladium in an SNS manner (Fig. 2). The figure shows that there is a pseudo-C2 symmetry along N1-Pd1-Cl1 axis, and the side view clearly shows that the two pyridyl groups are located at the axial positions; therefore, the isomer can be denominated as 2-rac(ax,ax)-SNS. The solid-state structure of 4 revealed that PSMePy coordinates in a rac(ax,ax)-SNS manner as well (Fig. 3). The selected bond distances, angles, and absolute dihedral angles for 2 and 4 are listed in Table 1. Pd–S and Pd–N bonds in 4 are slightly longer than those in 2 by ca. 0.01–0.04 Å. The averaged dihedral angle of N1–Pd1–S1–C3 and N1–Pd1–S2–C4 in 4 is 84.5°, which is smaller than that in 2 (95.2°) by 10.7°, probably because of the considerable steric hindrance between the two pyridyl groups in PSMePy and the bulky PPh₃ in 4. Comparison of the combined dihedral angle of N1–Pd1–S1–C1 and N1–Pd1–S2–C2 in 4 (35.7°) with that in 2 (20.2°) shows that the conformation of the palladacycle moieties in 4 is more distorted than in 2. This could also be attributable to the aforementioned difference between the steric hindrance in 2 and 4. One of the two pyrimidyl
groups in 4 is rotated significantly further inward than the other one, and therefore, it has an intramolecular face-to-face $\pi/\pi$ interaction (ca. 3.2 Å, 8.2°) with a phenyl group in PPh$_3$.

Fig. 2 Solid-state structure of 2 (upper, skew view; lower, side view). Thermal ellipsoids are shown at the 50% probability level. Hydrogen atoms and a counter anion are omitted for clarity.
Fig. 3 Solid-state structure of 4 (upper, skew view; lower, side view). Thermal ellipsoids are shown at the 50% probability level. Hydrogen atoms and counter anions are omitted for clarity.

Table 1 Selected Bond Distances (Å), Angles (deg) and Absolute Dihedral Angles (deg) for Complexes 2 and 4

<table>
<thead>
<tr>
<th></th>
<th>Complex 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd1–C11</td>
<td>2.2879(17)</td>
</tr>
<tr>
<td>Pd1–S1</td>
<td>2.2874(19)</td>
</tr>
<tr>
<td>Pd1–S2</td>
<td>2.2952(2)</td>
</tr>
<tr>
<td>Pd1–N1</td>
<td>2.0290(5)</td>
</tr>
<tr>
<td>Pd1–S1–C1</td>
<td>98.1(2)</td>
</tr>
<tr>
<td>Pd1–S1–C3</td>
<td>101.3(2)</td>
</tr>
</tbody>
</table>
Observation of equilibria among meso-SNS, rac-SNS, and NNN isomers in solution. Effects of temperature and steric and electronic factors of the ligands on the formation ratios

Although the X-ray crystallography for 2 and 4 revealed that these complexes have rac-SNS structures in the solid state, $^1$H NMR analysis revealed that 1–4 have several species in solution, respectively. The $^1$H NMR spectrum of 1 measured in CD$_3$OD at room temperature showed a total of 10 signals in the range of 7–10 ppm (Fig. 4). Variable temperature $^1$H NMR measurements and a COSY spectrum of 1 (see Supporting Information) indicate that two complexes exist in a ratio of approximately 1:1 at room temperature, and that they correspond to SNS and NNN isomers, respectively. The signal at 9.53 ppm, which is shifted to a considerably lower field, can be assigned to H$_e$ in 1-NNN, next to the coordinated N atoms. The signals at 8.62 and 8.77 ppm can be assigned, respectively, to H$_e$ in 1-NNN and H$_e'$ in 1-SNS, which are the protons next to the non-coordinated N atoms in the pyrimidyl groups. The doublet signals at 7.28 and 4.76 ppm ($J = 15.0$ Hz) are assignable to methylene protons in 1-NNN. The characteristic downfield signal of the former doublet should correspond to the inner proton close to Pd atom. In contrast, the signal of the methylene protons in 1-SNS appears at 5.28 ppm as a broad singlet, suggesting the existence of dynamic behavior.
The SNS isomer can have either rac- or meso-conformation via S-inversion, which is known to readily occur at room temperature in the NS and SCS-pincer palladium complexes. In the $^1$H NMR spectrum of 1, the 1-rac-SNS and 1-meso-SNS isomers could not be observed separately even at low temperature, probably because of the rapid S-inversion (Fig. 4). The ratio of 1-SNS to 1-NNN was significantly influenced by the analytical temperature, an effect that was revealed by variable temperature $^1$H NMR measurements (Fig. 5). The ratio was 0.23:0.77 at $-30 \, ^\circ\text{C}$, which was inverted at temperatures higher than room temperature (e.g., 0.67:0.33 at 50 °C). These results indicate that, in solution, complex 1 is in equilibrium among the meso-SNS, rac-SNS, and NNN isomers (Scheme 3). The van’t Hoff plot for the equilibrium between 1-SNS and 1-NNN afforded the thermodynamic parameters $\Delta H^\circ = -3.6 \pm 0.2$ kcal mol$^{-1}$ and $\Delta S^\circ = -12 \pm 1$ cal mol$^{-1}$ K$^{-1}$, respectively (see Supporting Information). The negative $\Delta S^\circ$ value would be attributable to the flexible structure of 1-SNS, i.e., free rotation of two aromatic ipso carbon-sulfur bonds, S-inversion, and ring inversion of the palladacycles, whereas the structure of 1-NNN is more rigid and has a lower degree of freedom because these dynamic behaviors are prohibited (Fig. 6).
Scheme 3 Equilibrium among 1-meso-SNS, 1-rac-SNS, and 1-NNN Isomers.

Fig. 6 Difference in the degree of freedom between 1-SNS and 1-NNN isomers.

Moreover, both 2-SNS and 2-NNN were observed in complex 2, using $^1$H NMR in CD$_3$CN. The population of 2-NNN was increased by lowering the temperature (similar to 1), whereas the SNS isomers were predominant over the NNN isomer over a temperature range of -30 to 40 °C (Fig. 7). Although the coordination ability of pyridine is generally higher than that of pyrimidine in terms of electronic factor, the coordination ability of the sulfur atoms in PySMePy is also higher than that of the sulfur atoms in PSMMePy because of the lower electron-withdrawing effect of pyridyl groups. This could be one of the reasons why the population of the SNS isomer in 2 is higher than that in 1. In addition, coordination of pyridyl groups is entropically more unfavorable than that of pyrimidyl groups. In the case of 2, the rac-SNS and meso-SNS isomers could be distinguished as SNS-major and SNS-minor (or vice versa) by observing the methylene signals as independent doublets in the $^1$H NMR spectra measured at temperatures lower than -15 °C (major: δ 5.27 and 4.94, $J = 17.6$ Hz; minor: δ 5.55 and 4.99, $J = 17.6$ Hz at -40 °C). The ratio of 2-SNS-major to 2-SNS-minor was 0.44:0.12–0.49:0.13 (Fig. 7).
In complex 3, which has methyl groups at 4 and 6-positions of pyrimidine rings of 1, no NNN isomer was detected; only rac-SNS and meso-SNS isomers were observed. The ratio of 3-SNS-major to 3-SNS-minor in CD$_2$Cl$_2$ was between 0.94:0.06 and 0.88:0.12 in a temperature range of -90 to 20 °C. Because complex 4 also has the bulky ligand, PPh$_3$, no NNN isomer was formed. The ratio of 4-SNS-major to 4-SNS-minor was low, 0.69:0.31–0.72:0.28 in CD$_2$Cl$_2$ (at -40–0 °C) and 0.64:0.36–0.67:0.33 in CD$_3$OD (at -20–5 °C), respectively. These results could be attributable to the steric hindrance between the tridentate and monodentate ligands. This hindrance efficiently suppresses the formation of the corresponding NNN isomers (Fig. 8).

If SN or SNN-coordinated complexes are formed, the complexes should afford a series of complicated signals in $^1$H NMR spectra because the NSNSN ligand coordinates to palladium in an unsymmetrical manner unlike SNS or NNN-coordinated complexes. However, no such signals were observed in the NMR analysis of complexes 1–4. As related hemilabile behaviors of S,N-hybrid ligands, equilibria between SNS and SN isomers in palladium complexes with SNS ligands (2,6-bis(alkyl- or phenylsulfanyl)methyl)pyridine), and between SN and NS isomers in a palladium complex with a NSN ligand (bis(2-pyridylmethyl)sulfide), have been reported.\textsuperscript{22}
Kinetic information on dynamic behavior between meso-SNS and rac-SNS isomers

The variable temperature $^1$H NMR measurement for complexes 2–4 provided further kinetic information on the dynamic behavior between the rac-SNS and meso-SNS isomers in solution. In complexes 2 and 4, the experimentally obtained spectra for the methylene region (ca. 4.8–5.8 ppm) were successfully simulated (Figs. 9 and 10). As for 2, the influences of the equilibrium between 2-NNN and 2-SNS were simply excluded, although the line-shape analysis is potentially further complicated by them. The activation parameters for $S$-inversion in 2 and 4 obtained from the Eyring plots are listed in Table 2 (see also Supporting Information). The negative $\Delta S^\ddagger$ values, observed in all cases, indicate highly ordered transition states. In the case of 4, the use of CD$_3$OD instead of CD$_2$Cl$_2$ as a solvent slightly decreased $\Delta H^\ddagger$ values and increased $\Delta S^\ddagger$ values, respectively. This result may suggest a relatively efficient solvation of the transition states by CD$_3$OD molecules. Although we could not simulate the variable temperature $^1$H NMR spectra for complex 3, because the signals for the minor isomer were too small, similar changes in 2–4 were observed (Fig. 11).
Fig. 9 Variable-temperature $^1$H NMR experimental (left: 400 MHz, CD$_3$CN) and simulated (right) spectra for 2-SNS-major and 2-SNS-minor ($k$: major$\rightarrow$minor, $k_1$: minor$\rightarrow$major).

Fig. 10 Variable-temperature $^1$H NMR experimental (left: 400 MHz, CD$_2$Cl$_2$) and simulated (right) spectra for 4-SNS-major and 4-SNS-minor ($k$: major$\rightarrow$minor, $k_1$: minor$\rightarrow$major).

<table>
<thead>
<tr>
<th>Solvent</th>
<th>$\Delta H^\ddagger$ (kcal mol$^{-1}$)</th>
<th>$\Delta S^\ddagger$ (cal mol$^{-1}$ K$^{-1}$)</th>
<th>$\Delta G^\ddagger_{298}$ (kcal mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-SNS-major $\rightarrow$ minor</td>
<td>CD$_3$CN</td>
<td>5.3 ± 0.6</td>
<td>-35 ± 3</td>
</tr>
<tr>
<td>2-SNS-minor $\rightarrow$ major</td>
<td>CD$_3$CN</td>
<td>6.3 ± 0.7</td>
<td>-27 ± 3</td>
</tr>
<tr>
<td></td>
<td>CD$_2$Cl$_2$</td>
<td>CD$_3$OD</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>-------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td><strong>4-SNS-major → minor</strong></td>
<td>10.5 ± 1.0</td>
<td>-17 ± 4</td>
<td>15.6 ± 2.2</td>
</tr>
<tr>
<td></td>
<td>7.9 ± 0.4</td>
<td>-24 ± 2</td>
<td>15.1 ± 1.0</td>
</tr>
<tr>
<td><strong>4-SNS-minor → major</strong></td>
<td>9.5 ± 0.6</td>
<td>-18 ± 3</td>
<td>14.9 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>8.6 ± 1.0</td>
<td>-20 ± 4</td>
<td>14.6 ± 2.2</td>
</tr>
</tbody>
</table>

**Fig. 11** Variable temperature $^1$H NMR experimental spectra for 3-SNS-major and 3-SNS-minor (400 MHz, CD$_2$Cl$_2$ (left), CD$_3$OD (right)).

**Density functional study**

The relative thermodynamic stability of SNS, NNN, and SNN isomers; ring and $S$-inversions among SNS isomers; and equilibria between SNS and NNN isomers were theoretically investigated by the DFT method. The geometries of the stable complexes and transition states were optimized by the B3LYP method using a basis set composed of the combination of LANL2DZ for Pd and 6-31G(d) for all other atoms. The respective energy profiles ($\Delta G$) for the ring and $S$-inversions and the $S,N$-coordinating atom exchanges in 1 are shown in Figs. 12 and 13. As indicated in Fig. 12, although 1-rac(eq,eq)-SNS is slightly favorable compared with 1-rac(ax,ax)-SNS and 1-asymm(ax,eq)-SNS, these conformers have similar thermodynamic stability. Ring inversion causes the conformational exchange of both pyrimidyl groups on the sulfur atoms, while $S$-inversion induces the conformational exchange of one pyrimidyl group. The respective activation energy barriers for ring inversions between 1-rac(ax,ax)-SNS and 1-rac(eq,eq)-SNS and between 1-asymm(ax,eq)-SNS and 1-asymm(eq,ax)-SNS are distinctly low (not greater than 2.0 kcal mol$^{-1}$). This is consistent with the experimental result that no conformers were independently observed by $^1$H NMR measurements even at low temperature, i.e., the ring inversions are
significantly fast on the NMR time scale, as previously reported for $[\text{MCl}_2(\text{NS})]^{30}$ (M = Pd, Pt) and $[\text{MX(SCS)}]^{49}$ (M = Ni, Pd, Pt; X = Cl, Br) complexes. The chemical species, denominated as 1-rac-SNS and 1-meso-SNS in Scheme 1, correspond to the averaged structures of 1-rac(ax,ax)-SNS and 1-rac(eq,eq)-SNS and 1-asymm(ax,eq)-SNS and 1-asymm(eq,ax)-SNS, respectively. The barriers for $S$-inversion were calculated to be 15.0–15.7 kcal mol$^{-1}$, which were roughly comparable to that in $[\text{PdCl}_2(\text{NS})]$ (NS = 2-(MeSCH$_2$)C$_5$H$_3$N), estimated to be 17.1 kcal mol$^{-1}$.$^{30}$

![Energy profile](image)

**Fig. 12** Energy profile ($\Delta G$, kcal mol$^{-1}$) for ring and $S$-inversions among 1-SNS isomers. Hydrogen atoms in the optimized structures are omitted for clarity.

As shown in Fig. 13, 1-NNN is thermodynamically more stable than 1-rac(ax,ax)-SNS by 2.1 kcal mol$^{-1}$. The interconversion between 1-rac(ax,ax)-SNS and 1-NNN was found to proceed through an intermediate complex, 1-ax-SNN, which is less stable than 1-rac(ax,ax)-SNS by 4.1 kcal mol$^{-1}$. The relative instability of 1-ax-SNN could be attributable to the ring strain of the fused 5- and 7-membered palladacycle moieties caused by SNN-tridentate coordination. Although we could not observe either these SNN intermediates or the dynamic behavior of the $S,N$-coordinating atom exchange, the energy
profile depicted in Fig. 13 appears to be consistent with the aforementioned experimental results, and the interconversion mechanism would be a reasonable explanation.

![Energy profile](image)

**Fig. 13** Energy profile ($\Delta G$, kcal mol$^{-1}$) for $S,N$-coordinating atom exchanges between 1-$rac(ax,ax)$-SNS and 1-NNN via an intermediate, 1-$ax$-SNN. Hydrogen atoms in the optimized structures are omitted for clarity.

The overall scheme for the equilibria among SNS, SNN, and NNN isomers for 1 and 2 is shown in Scheme 4 with the energy differences ($\Delta G$, kcal mol$^{-1}$) relative to either 1- or 2-$rac(ax,ax)$-SNS. The respective activation energy barriers for the ring inversions between 2-$rac(ax,ax)$-SNS and 2-$rac(eq,eq)$-SNS and between 2-$asymm(ax,eq)$-SNS and 2-$asymm(eq,ax)$-SNS are very low, similar to those for 1. The $S$-inversions for 2 via TS$_{S11}$ or TS$_{S12}$ have slightly greater barriers than those for 1 (15.9–16.5 kcal mol$^{-1}$ for 2 vs. 15.0–15.7 kcal mol$^{-1}$ for 1), and these values are roughly in agreement with experimentally obtained $\Delta G^\ddagger$ values for 2 shown in Table 2 (15.7 and 14.3 kcal mol$^{-1}$). The SNN and NNN isomers of 2 are more unstable than those of 1 by 3.0–3.5 kcal mol$^{-1}$. Although the calculated energy differences are somewhat greater, the difference corresponds to the ratio of SNS to NNN obtained by $^1$H NMR analysis (e.g. approximately 1:1 for 1 and 3.5:1 for 2 at 20 °C, see Figs. 5 and 7). Because the relative energy levels of TS$_{SNN-NNN2}$ for 1 and 2 are high, these equilibria seem to be prevented; therefore, the pathways from SNS to NNN via $ax$-SNN would be more dominant than those via $eq$-SNN in both 1 and 2.
Conclusion

Cationic divalent palladium complexes 1–4 having NSNSN ligands were synthesized and characterized. Though the NSNSN ligands in 2 and 4 were fixed as rac(ax,ax)-SNS in the solid state, the equilibria among meso-SNS, rac-SNS, and NNN isomers were observed in 1–4 in solution. The equilibrium between the SNS and NNN isomers could be modulated by temperature and the respective steric and electronic factors of tridentate and monodentate ligands. Variable temperature NMR measurements of 1 and 2 revealed that lowering the temperature made NNN isomers more predominant than SNS isomers. This observation is attributable to the difference in the degrees of freedom between the isomers, i.e., SNS isomers are flexible because of ring inversion, S-inversion, and free rotation of heteroaromatic ipso C–S bonds, while the NNN isomers are rigid and have no such dynamic behaviors. The steric demand between the tridentate and monodentate ligands in 3 and 4 were found to shift the equilibrium from NNN to SNS isomers. That is, the free basic nitrogen moieties adjacent to the metal center can be available by introducing steric bulkiness. Introduction of pyridyl groups instead of pyrimidyl groups as N-heteroarenes also shifted the equilibrium to SNS isomers. The activation parameters for S-inversion in 2 and 4 suggested highly ordered transition states. DFT calculations indicated very rapid ring inversions, relatively slow S-inversions in SNS complexes, and a stepwise S,N-coordinating atom-exchange mechanism. The latter governed the isomerization between the SNS and NNN isomers via a relatively unstable, distorted ax-SNN intermediate. The fundamental information obtained here about the behavior of palladium complexes having NSNSN ligands may be helpful to promote an increase in reactivity.
toward small molecules by taking advantage of the hemilability and the proximity between the metal center and the free basic moieties.

**Experimental**

**Materials and methods**

All manipulations were performed under an argon atmosphere using standard Schlenk techniques. Dry solvents were purchased from either Wako Chemical or Nacalai. Flash column chromatography was performed using silica gel SILICYCLE SiliaFlash F60 (40-63 μm, 230-400 mesh).

**Physical and analytical measurements**

NMR spectra were recorded on either a JEOL AL-400 (400 MHz (\(^1\)H), 100 MHz (\(^{13}\)C)) or a Bruker AV-300N (300 MHz (\(^1\)H), 75 MHz (\(^{13}\)C)) spectrometer. Chemical shift values (δ) were expressed relative to SiMe₄. Zero filling and apodization were not applied to all the FIDs. IR measurements (ATR) were carried out using a JASCO FT/IR-6100 spectrometer. Elemental analysis was obtained using a J-SCIENCE LAB JM-10 analyzer. Mass spectra were recorded on either a JEOL JMS-T100LC or a SHIMADZU GCMS-QP5050 spectrometer. Melting points were measured on a Yanagimoto micro melting point apparatus.

**Synthesis of NSNSN ligands**

PSMePy, PySMePy and dmPSMePy were synthesized in a similar manner. The following procedure for PSMePy is representative.

**PSMePy.** To a mixture of 2-mercaptopyrimidine (277 mg, 2.47 mmol) and NaOMe (155 mg, 2.86 mmol), dry ethanol (8 mL) was added and the reaction mixture was stirred at room temperature for 1 h. 2,6-Bis(chloromethyl)pyridine (200 mg, 1.13 mmol) was then added and the mixture was stirred at 70 °C for 24 h. Toluene was poured into the reaction mixture, and the precipitates were removed by filtration. The filtrate was dried under vacuum, and the obtained crude compound was purified by silica gel column chromatography (eluent: hexane/ethyl acetate = 1:3) to give PSMePy (356 mg, 1.09 mmol) in 96% isolated yield as a white solid.

\[^1\]H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 8.50 (d, \(J = 4.8\) Hz, 4H, Pym-4,6), 7.52 (t, \(J = 7.8\) Hz, 1H, Py-4), 7.35 (d, \(J = 7.8\) Hz, 2H, Py-3,5), 6.95 (t, \(J = 4.8\) Hz, 2H, Pym-5), 4.54 (s, 4H, CH\(_2\)). \(^{13}\)C NMR (100 MHz, CDCl\(_3\)) \(\delta\) 171.9 (Pym-2), 157.3 (Py-2,6), 157.2 (Pym-4,6), 137.1 (Py-4), 121.4 (Py-3,5), 116.6 (Pym-5), 36.9 (CH\(_2\)). The other data were consistent with those reported previously.

**PySMePy.** White solid (359 mg, 1.10 mmol, 97% isolated yield), mp 94–96 °C. \(^1\)H NMR (300 MHz, CDCl\(_3\)) \(\delta\) 8.40 (ddd, \(J = 4.9, 1.9, 1.0\) Hz, 2H, terminal Py-6), 7.47 (t, \(J = 7.7\) Hz, 1H, central Py-4), 7.43 (ddd, \(J = 8.1, 7.3, 1.9\) Hz, 2H, terminal Py-4), 7.28 (d, \(J = 7.7\) Hz, 2H, central Py-3,5), 7.18 (dt, \(J = 8.1, 1.0\) Hz, 2H, terminal Py-3), 6.94 (ddd, \(J = 7.3, 4.9, 1.0\) Hz, 2H, terminal Py-5), 4.53 (s, 4H, CH\(_2\)). \(^{13}\)C
NMR (75 MHz, CDCl$_3$) $\delta$ 158.4 (terminal Py-2), 157.7 (central Py-2,6), 149.3 (terminal Py-6), 137.1 (central Py-4), 136.0 (terminal Py-4), 121.9 (terminal Py-3), 121.4 (central Py-3,5), 119.5 (terminal Py-5), 36.0 (CH$_2$). Anal. Caled for C$_{17}$H$_{15}$N$_3$S$_2$: C, 62.74; H, 4.65; N, 12.91. Found: C, 62.55; H, 4.54; N, 12.82.

dmPSMePy. White solid (418 mg, 1.09 mmol, 94% isolated yield), mp 147–149 °C. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 7.48 (dd, $J = 8.4$, 6.9 Hz, 1H, Py-4), 7.34 (br d, $J = 7.8$ Hz, 2H, Py-3,5), 6.66 (s, 2H, Pym-5), 4.54 (s, 4H, CH$_2$), 2.37 (s, 12H, CH$_3$). $^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 170.5 (Pym-2), 167.0 (Pym-4,6), 157.9 (Py-2,6), 136.8 (Py-3,5), 121.4 (Py-4), 115.8 (Pym-5), 36.9 (CH$_2$), 23.9 (CH$_3$). Anal. Caled for C$_{19}$H$_{21}$N$_3$S$_2$: C, 59.50; H, 5.52; N, 18.26. Found: C, 59.69; H, 5.58; N, 18.32.

**Synthesis of complexes 1–3**

Complexes 1–3 were synthesized in a similar manner. The following procedure for 1 is representative.

**[PdCl(PSMePy)](OTf) (1).** To a mixture of [PdCl$_2$(MeCN)$_2$] (20.1 mg, 0.078 mmol), PSMePy (25.4 mg, 0.078 mmol), and AgOTf (20.2 mg, 0.079 mmol), dry acetonitrile (2 mL) was added and the reaction mixture was stirred at room temperature for 3 h. After filtration, diethyl ether was added to the orange filtrate to precipitate. The supernatant solution was removed and the precipitate was dried under vacuum. Recrystallization from acetonitrile/diethyl ether gave orange needle-like crystals (40.6 mg, 0.066 mmol) in 85% isolated yield. Mp 186–188 ºC (dec.). $^1$H NMR for 1-NNN (300 MHz, CD$_2$OD) $\delta$ 9.53 (dd, $J = 6.1$, 2.1 Hz, 2H, Pym-6), 8.62 (dd, $J = 4.5$, 2.1 Hz, 2H, Pym-4), 8.14 (t, $J = 7.9$ Hz, 1H, Py-4), 7.78 (d, $J = 7.8$ Hz, 2H, Py-3,5), 7.32 (dd, $J = 6.1$, 4.5 Hz, 2H, Pym-5), 7.28 (d, $J = 15.0$ Hz, 2H, CH$_2$), 4.76 (d, $J = 15.0$ Hz, 2H, CH$_2$). $^1$H NMR for 1-NNN (300 MHz, CD$_3$CN) $\delta$ 9.34 (dd, $J = 6.3$, 2.1 Hz, 2H, Pym-6), 8.57 (dd, $J = 4.5$, 2.1 Hz, 2H, Pym-4), 8.06 (m, 1H, Py-4), 7.67 (d, $J = 8.1$ Hz, 2H, Py-3,5), 7.29 (dd, $J = 6.3$, 4.5 Hz, 2H, Pym-5), 7.06 (d, $J = 14.7$ Hz, 2H, CH$_2$), 4.62 (d, $J = 14.7$ Hz, 2H, CH$_2$). $^1$H NMR for 1-SNS (300 MHz, CD$_2$OD) $\delta$ 8.77 (d, $J = 4.9$ Hz, 4H, Pym-4,6), 8.16 (t, $J = 7.9$ Hz, 1H, Py-4), 7.79 (d, $J = 7.9$ Hz, 2H, Py-3,5), 7.53 (t, $J = 4.9$ Hz, 2H, Pym-5), 5.28 (br s, 4H, CH$_2$). $^1$H NMR for 1-SNS (300 MHz, CD$_3$CN) $\delta$ 8.72 (d, $J = 4.8$ Hz, 4H, Pym-4,6), 8.06 (m, 1H, Py-4), 7.69 (d, $J = 7.8$ Hz, 2H, Py-3,5), 7.49 (t, $J = 4.8$ Hz, 2H, Pym-5), 5.07 (br s, 4H, CH$_2$). $^{13}$C NMR for 1-NNN (75 MHz, CD$_3$CN) $\delta$ 171.0 (Pym-2), 163.8 (Pym-4), 160.6 (Pym-6), 159.4 (Py-2,6), 145.0 (Py-4), 125.6 (Py-3,5), 119.3 (Pym-5), 38.0 (CH$_2$). $^{13}$C NMR for 1-SNS (75 MHz, CD$_3$CN) $\delta$ 163.2 (Pym-2), 160.6 (Pym-4,6), 159.2 (Py-2,6), 141.8 (Py-4), 123.6 (Py-3,5), 122.6 (Pym-5), 47.1 (CH$_2$). Anal. Caled for C$_{18}$H$_{13}$ClF$_3$N$_3$O$_2$PdS$_3$: C, 31.08; H, 2.12; N, 11.33 Found: C, 31.38; H, 2.21; N, 11.34.

**[PdCl(PSMePy)](OTf) (2).** Orange solid (110 mg, 0.18 mmol, 94% isolated yield), mp 190–192 ºC (dec.). $^1$H NMR for 2-NNN (300 MHz, CD$_3$CN) $\delta$ 9.17 (dd, $J = 6.0$, 1.0 Hz, 2H, terminal Py-6), 7.98 (t, $J = 7.8$ Hz, 1H, central Py-4), 7.75–7.67 (m, 2H, terminal Py-4), 7.60 (d, $J = 8.0$ Hz, 2H, central Py-3,5), 7.45 (m, 2H, terminal Py-3), 7.28 (ddd, $J = 7.4$, 6.0, 1.4 Hz, 2H, terminal Py-5), 6.89 (d, $J = 14.7$ Hz, 2H, CH$_2$), 4.63 (d, $J = 14.7$ Hz, 2H, CH$_2$). $^1$H NMR for 2-SNS (300 MHz, CD$_3$CN) $\delta$ 8.47 (d, $J = 4.7$ Hz,
2H, terminal Py-6), 8.08 (t, \( J = 8.0 \) Hz, 1H, terminal Py-4), 7.88 (br s, 4H, terminal Py-3,4), 7.68 (d, \( J = 8.0 \) Hz, 2H, terminal Py-3,5), 7.45 (br s, 2H, terminal Py-5), 5.33 (br s, 2H, \( CHH \)), 5.11 (br s, 2H, \( CHH \)).

Selected \(^1\)H NMR for 2-SNS-major (400 MHz, CD\(_2\)CN, -40 °C) \( \delta \) 5.27 (d, \( J = 17.6 \) Hz, 2H, \( CHH \)), 4.94 (d, \( J = 17.6 \) Hz, 2H, \( CHH \)). Selected \(^1\)H NMR for 2-SNS-minor (400 MHz, CD\(_2\)CN, -40 °C) \( \delta \) 5.55 (d, \( J = 17.6 \) Hz, 2H, \( CHH \)), 4.99 (d, \( J = 17.6 \) Hz, 2H, \( CHH \)).

\(^{13}\)C NMR for 2-NNN (75 MHz, CD\(_2\)CN) \( \delta \) 159.0 (terminal Py-2), 158.6 (central Py-2,6), 156.2 (terminal Py-6), 144.4 (central Py-4), 140.4 (terminal Py-4), 128.9 (terminal Py-3), 125.8 (central Py-3,5), 123.5 (terminal Py-5), 37.2 (CH\(_2\)).

\(^{13}\)C NMR for 2-SNS (75 MHz, CD\(_2\)CN) \( \delta \) 164.2 (central Py-2,6), 151.9 (terminal Py-6), 149.0 (terminal Py-2), 141.7 (central Py-4), 139.8 (terminal Py-4), 127.2 (terminal Py-3), 126.0 (terminal Py-5), 123.6 (central Py-3,5), 45.9 (CH\(_2\)).

Anal. Calcd for C\(_{18}\)H\(_{16}\)Cl\(_2\)N\(_3\)O\(_3\)PdS\(_3\): C, 35.07; H, 2.45; N, 6.82. Found: C, 35.14; H, 2.60; N, 6.71.

**[PdCl(dmpPSMePy)](OTf)** (3). Orange needle-like crystals (40.5 mg, 0.060 mmol, 77% isolated yield), mp 179–183 °C (dec.). \(^1\)H NMR for 3-SNS-major (400 MHz, CD\(_2\)Cl\(_2\)) \( \delta \) 8.14 (t, \( J = 8.4 \) Hz, 1H, Py-4), 7.79 (d, \( J = 8.4 \) Hz, 2H, Py-3,5), 7.10 (s, 2H, Pym-5), 5.18 (d, \( J = 17.4 \) Hz, 2H, \( CHH \)), 4.94 (d, \( J = 17.4 \) Hz, 2H, \( CHH \)).

Selected \(^1\)H NMR for 3-SNS-minor (400 MHz, CD\(_2\)Cl\(_2\)) \( \delta \) 5.56, 5.02.

\(^{13}\)C NMR for 3-SNS-major (75 MHz, CD\(_2\)Cl\(_2\)) \( \delta \) 171.0 (Pym-4,6), 163.3 (Py-2,6), 161.1 (Pym-2), 141.6 (Py-4), 123.7 (Py-3,5), 121.2 (Pym-5), 47.0 (CH\(_2\)), 24.2 (CH\(_3\)).

Anal. Calcd for C\(_{20}\)H\(_{21}\)Cl\(_3\)N\(_3\)O\(_3\)PdS\(_3\): C, 34.34; H, 3.09; N, 9.77. Found: C, 34.37; H, 3.31; N, 9.61.

**Synthesis of [Pd(PSMePy)(PPh\(_3\))](OTf)\(_2\)** (4)

To a dry dichloromethane solution (1 mL) of [PdCl(MeCN)\(_2\)] (20.1 mg, 0.078 mmol), a dichloroethane solution of PPh\(_3\) (4.08 mL, 0.077 mmol) was added at room temperature. After 15 min, PSMePy (25.3 mg, 0.077 mmol) and AgOTf (40.4 mg, 0.157 mmol) were added to the reaction mixture. After 3 h, the yellow suspension was filtered, and the resulting filtrate was vacuumed to dry. The obtained solid was recrystallized from dry dichloromethane/hexane, and the yellow rhombic crystals were obtained (63.6 mg, 0.064 mmol, 83% isolated yield). Mp 203–205 °C (dec.). \(^1\)H NMR for 4-SNS-major (400 MHz, CD\(_2\)Cl\(_2\), -60 °C) \( \delta \) 8.36 (d, \( J = 4.8 \) Hz, 4H, Pym-4,6), 7.99 (t, \( J = 8.0 \) Hz, 1H, Py-4), 7.90 (dd, \( J = 12.8, 7.5 \) Hz, 6H, Ph), 7.69–7.55 (m, 5H, Py-3,5 and Ph), 7.52 (dt, \( J = 7.5, 2.9 \) Hz, 6H, Ph), 7.29 (t, \( J = 4.8 \) Hz, 2H, Pym-5), 5.67 (d, \( J = 16.8 \) Hz, 2H, \( CHH \)), 5.01 (d, \( J = 16.8 \) Hz, 2H, \( CHH \)).

\(^1\)H NMR for 4-SNS-minor (400 MHz, CD\(_2\)Cl\(_2\), -60 °C) \( \delta \) 8.34 (d, \( J = 4.8 \) Hz, 4H, Pym-4,6), 8.08 (t, \( J = 8.0 \) Hz, 1H, Py-4), 7.71 (dd, \( J = 12.8, 7.6 \) Hz, 6H, Ph), 7.69–7.55 (m, 5H, Py-3,5 and Ph), 7.45 (dt, \( J = 7.6, 2.8 \) Hz, 6H, Ph), 7.34 (t, \( J = 4.8 \) Hz, 2H, Pym-5), 5.45 (d, \( J = 16.8 \) Hz, 2H, \( CHH \)), 5.37 (d, \( J = 16.8 \) Hz, 2H, \( CHH \)).

\(^{13}\)C NMR for 4-SNS-major (100 MHz, CD\(_2\)Cl\(_2\), -40 °C) \( \delta \) 161.2 (Py-2,6), 161.0 (d, \( J_{C-P} = 3.0 \) Hz, Pym-2), 159.5 (Pym-4,6), 140.9 (Py-4), 135.1 (d, \( J_{C-P} = 10.8 \) Hz, Ph), 133.0 (d, \( J_{C-P} = 3.1 \) Hz, Ph), 129.4 (d, \( J_{C-P} = 12.0 \) Hz, Ph), 126.4 (d, \( J_{C-P} = 57.7 \) Hz, Ph), 122.6 (Py-3,5), 122.1 (Pym-5), 47.7 (d, \( J_{C-P} = 5.0 \) Hz, CH\(_2\)).

\(^{13}\)C NMR for 4-SNS-minor (100 MHz, CD\(_2\)Cl\(_2\), -40 °C) \( \delta \) 161.5 (Py-2,6), 160.8 (d, \( J_{C-P} = 5.0 \) Hz, CH\(_2\)).
Refinements were continued - consisted of the combination of LANL2DZ basis set for Pd and the Lee–Yang–Parr correlation functional (LYP) on a SGI Altix UV100 system at Nara Women’s University. The basis set consisted of the combination of LANL2DZ for Pd and the 6-31G(d) basis set for all other atoms. No constraints were imposed for any of the systems. Frequency calculations on optimized species established that the energy minima possessed only real frequencies and the transition states possessed a single imaginary frequency. Zero-point energy and thermodynamic functions were computed at standard temperature (298.15 K) and pressure (1 atm). Spatial plots of the

Crystallographic study of complexes 2 and 4
Crystals suitable for X-ray diffraction measurements obtained by recrystallization from CH$_2$CN/Et$_2$O for 2 (orange crystals) and CH$_2$Cl$_2$/hexane for 4 (yellow crystals) were mounted using a cryoloop. The diffraction data were collected with a Rigaku Saturn CCD detector (Mo$_{K\alpha}$, $\lambda = 0.71073$ Å). Crystal data and experimental data are listed in Supporting Information. The structures were solved by direct methods using SHELXS-97 and refined by least squares on $F^2$, SHELXL-2013. Non-hydrogen atoms were anisotropically refined except for disordered triflate anions. Refinements were continued until all shifts were smaller than one-tenth of the standard deviations of the parameters involved. Atomic scattering factors and anomalous dispersion terms were taken from the International Tables for X-ray Crystallography.

Dynamic NMR simulation for complexes 2 and 4
The multispin dynamic NMR simulations were performed using DNMR (Dynamic NMR) Lineshape Fitting module equipped in Bruker TopSpin software. The simulation pattern of $2 \times 2$-spin was selected, in which four exchangeable protons, H$_a$ and H$_b$ (for CH$_2$ in SNS-major), and, H$_{a'}$ and H$_{b'}$ (for CH$_2$ in SNS-minor), were considered. These protons were postulated to be exchanged one another (H$_a$$\leftrightarrow$H$_a$$\leftrightarrow$H$_b$$\leftrightarrow$H$_b$$\leftrightarrow$H$_a$) at the different rates $k$ (major$\rightarrow$minor) and $k_1$ (minor$\rightarrow$major). The coupling constants of the germinal protons were fixed, and the ratios of major to minor were not. The natural line width for each spectrum was determined on the basis of the measurement of non-exchanging peaks of the complexes.

Theoretical calculations
To consistently compare the single-point energies of model complexes, calculations were carried out using density functional theory (DFT)-optimized geometries. Calculations were performed using the Gaussian 09 Rev. B.01 implementation of B3LYP [Becke three-parameter exchange functional (B3)] and the Lee–Yang–Parr correlation functional (LYP) on a SGI Altix UV100 system at Nara Women’s University. The basis set consisted of the combination of LANL2DZ for Pd and the 6-31G(d) basis set for all other atoms. No constraints were imposed for any of the systems. Frequency calculations on optimized species established that the energy minima possessed only real frequencies and the transition states possessed a single imaginary frequency. Zero-point energy and thermodynamic functions were computed at standard temperature (298.15 K) and pressure (1 atm). Spatial plots of the
optimized geometries were obtained from Gaussian 09 output using Cambridge Soft Corporation’s ChemBio3D Ultra ver. 11.0.1.

Electronic supplementary information
Electronic supplementary information (ESI) available: The COSY spectrum for 1-NNN and 1-SNS, the van’t Hoff plot for the equilibrium between 1-NNN and 1-SNS, the Eyring plots for 2 and 4, crystal data for 2 and 4, optimized geometries and energies for 1 and 2, and CIF files for 2 and 4. CCDC reference numbers 942653 (2) and 942654 (4). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c3dt51592c

Acknowledgements
This work was supported by Grant-in-Aid for Scientific Research on Innovative Areas (Molecular Activation Directed toward Straightforward Synthesis) from The Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. We thank prof. Takashi Kajiwara (Nara Women’s University) for supporting our X-ray crystallography. Ms. Reina Shimokawa (NWU) is also acknowledged for her help synthesizing palladium complexes.

Notes and References

3952-3957.


