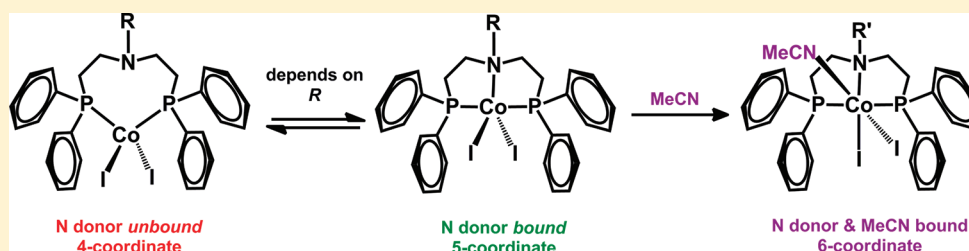


## Dual Coordination Modes of Ethylene-Linked NP2 Ligands in Cobalt(II) and Nickel(II) Iodides

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## Supporting Information

## ABSTRACT:



Here we report the syntheses and crystal structures of a series of cobalt(II) and nickel(II) complexes derived from  $R$ NP2 ligands (where  $R = \text{OMe}_{Bz}, \text{H}_{Bz}, \text{Br}_{Bz}, \text{Ph}$ ) bearing ethylene linkers between a single N and two P donors. The  $\text{Co}^{\text{II}}$  complexes generally adopt a tetrahedral configuration of general formula  $[(\text{NP2})\text{Co}(\text{I})_2]$ , wherein the two phosphorus donors are bound to the metal center but the central N-donor remains unbound. We have found one case of structural isomerism within a single crystal structure. The  $\text{Co}^{\text{II}}$  complex derived from  $Bz$ NP2 displays dual coordination modes: one in the tetrahedral complex  $[(Bz\text{NP2})\text{Co}(\text{I})_2]$ ; and the other in a square pyramidal variant,  $[(Bz\text{NP2})\text{Co}(\text{I})_2]$ . In contrast, the  $\text{Ni}^{\text{II}}$  complexes adopt a square planar geometry in which the  $\text{P}(\text{Et})\text{N}(\text{Et})\text{P}$  donors in the ligand backbone are coordinated to the metal center, resulting in cationic species of formula  $[(R\text{NP2})\text{Ni}(\text{I})]^+$  with iodide as counterion. All  $\text{Ni}^{\text{II}}$  complexes exhibit sharp  $^1\text{H}$  and  $^{31}\text{P}$  spectra in the diamagnetic region. The  $\text{Co}^{\text{II}}$  complexes are high-spin ( $S = 3/2$ ) in the solid state as determined by SQUID measurements from 4 to 300 K. Solution electron paramagnetic resonance (EPR) experiments reveal a high-spin/low-spin  $\text{Co}^{\text{II}}$  equilibrium that is dependent on solvent and ligand substituent.

## INTRODUCTION

Complexes containing late transition metals bound to phosphine donors have found application in a wide variety of industrial transformations and synthetic methodologies. Phosphorus ligands are of interest because they stabilize low oxidation states ( $M^{\text{II/I}}$ ) that are active species in many catalytic cycles, and cobalt phosphines promote ethylene polymerization<sup>1</sup> and hydroformylation reactions.<sup>2–4</sup> Synthetically, there is ongoing interest in substituting palladium with more earth abundant metals such as nickel in C–C bond forming reactions.<sup>5–7</sup> Chelating trisphosphines bearing different anionic heteroatoms have been employed to shed light on ligand field effects for both anionic and neutral phosphines.

In the case of mixed phosphorus- and nitrogen-containing ligands, the additional functionality of an N-donor can allow the metal center to access a greater range of oxidation states than with phosphines alone. For example, cobalt and nickel complexes derived from pyridine-containing phosphine ligands often are

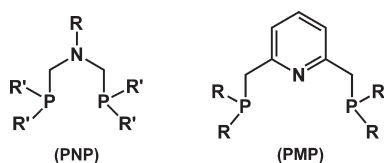
more efficient ethylene polymerization catalysts.<sup>1,8</sup> Other investigators have used multidentate ligands bearing groups presenting “mismatched” donor strengths, as in those containing a wider variety of hard (N,O) and soft (P,S) donors.<sup>9</sup> Inclusion of nitrogen atoms in predominantly phosphine-based ligands has led to the development of efficient dihydrogen ( $\text{H}_2$ ) evolution and oxidation catalysts containing both nickel and cobalt.<sup>10</sup> In each case, researchers recognized that the structural and coordination properties of a chosen ligand to a given metal center dictate the reactivity and magnetic properties of the resulting complex.

Three main types of  $P_xN_y$  ligands differ on the basis of structural flexibility and linker type.<sup>11</sup> In the case of the pyridine-based PMP ligand (Scheme 1), the structural rigidity of the pyridine ring enforces binding of the N-donor to the metal

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Scheme 1

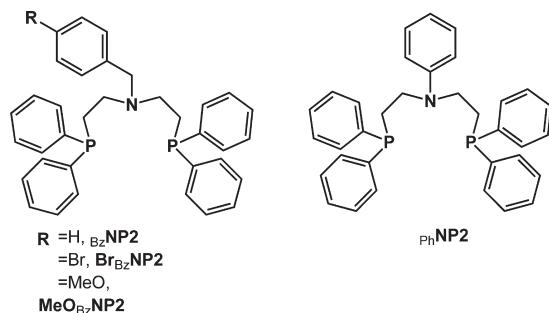


center.<sup>8,12,13</sup> Coordination of the P- and N-donors in **PMP** results in 5-membered ring chelates that are thermodynamically stable. For example, Rieger and co-workers prepared trigonal bipyramidal complexes  $[(\text{PMP})\text{Co}^{\text{II}}(\text{Cl})_2]$  and  $[(\text{PMP})\text{Fe}^{\text{II}}(\text{Cl})_2]$  in which the entire P–N–P donor set binds to the metal centers.

In contrast, the ligand **PNP** contains a methylene linker between the N- and P-atoms, which disfavors simultaneous coordination of the three donor atoms. DuBois and co-workers synthesized several  $\text{Ni}^{\text{II}}$  complexes derived from ligands of general formula  $\text{R}_1\text{P}-\text{N}(\text{R}_2)-\text{PR}_1$  ( $\text{R}_1 = \text{Et}$ ;  $\text{R}_2 = \text{Me}, n\text{Bu}$ ). The resulting structures adopt slightly distorted square planar geometries that display only P-coordination, while the nitrogen remains unbound. More recent work utilizing  $\text{Co}^{\text{II}}$  led to the isolation of  $[(\text{PNP})\text{Co}^{\text{II}}(\text{MeCN})_3]$ ,<sup>14,15</sup> which also excludes the N-donor from the coordination sphere. Further work using methylene-linked cyclic ligands (**P2N2**) produced complexes in which phosphorus atoms are bound to  $\text{Ni}^{\text{II}}$  and  $\text{Co}^{\text{II}}$  centers.

Here we report work on complexes of **NP2** ligands that retain the stable 5-membered chelates found in **PMP** but impart structural flexibility by using ethylene linkers instead of a rigid pyridyl moiety (Scheme 2). Hii and co-workers found that metalation of **NP2** ligands ( $\text{RNP2}$ ;  $\text{R} = t\text{Bu}, \text{Ph}, 4\text{-OMeC}_6\text{H}_4$ ) with  $\text{Pd}^{\text{II}}$  salts afforded N-bound complexes  $[(\text{RNP2})\text{Pd}^{\text{II}}(\text{Cl})_2]$ , whereas treatment with a  $\text{Pd}^0$  starting material produced only P-bound  $[(\text{RNP2})\text{Pd}(\text{dba})]$  (as determined by  $^{31}\text{P}$  shifts).<sup>16</sup> Of interest is whether ligation/deligation of the N-donor is attributable to electronic factors associated with the change in oxidation state  $\text{Pd}^{\text{II}} \rightarrow \text{Pd}^0$ , or to a simple geometric preference of square planar  $\text{Pd}^{\text{II}}$  for the N-donor.

Scheme 2



We have investigated **NP2** complexes of two transition metals in the same oxidation state ( $\text{Ni}^{\text{II}}$  and  $\text{Co}^{\text{II}}$ ) that typically adopt different coordination geometries (square planar and tetrahedral, respectively). Here we report that **NP2** ligands with *para*-substituted benzylamines and aniline as N-substituent can adopt dual binding motifs when bound to  $\text{Co}^{\text{II}}$ , designated **NP2** and **NP2**, where the donor atoms are underlined. We have explored

the solid and solution state properties of the  $\text{Co}^{\text{II}}$  complexes by X-ray, superconducting quantum interference device (SQUID), and electron paramagnetic resonance (EPR) methods. The corresponding  $\text{Ni}^{\text{II}}$  complexes are all square planar with **NP2** coordination.

## EXPERIMENTAL SECTION

**Reagents and General Procedures.** Benzylamine, bromobenzylamine, 2-bromoethanol and phosphorus tribromide ( $\text{PBr}_3$ ) were used as received from Sigma-Aldrich. The anhydrous metal salts cobalt(II) iodide and nickel(II) iodide also were obtained from Sigma-Aldrich, while diphenylphosphine ( $\text{Ph}_2\text{PH}$ ) was from Strem. The **PNP** ligand  $^{\text{Ph}_2}\text{P}(^{\text{Ph}}\text{N})\text{P}^{\text{Ph}_2}$  was synthesized according to a published procedure.<sup>17</sup> Solvents (MeCN, THF,  $\text{Et}_2\text{O}$ , toluene and hexane) were obtained from a solvent purification system employing the Grubbs method,<sup>18</sup> while acetone from J.T. Baker was used without further purification. Deuterated solvent ( $\text{CDCl}_3$ ) was from Cambridge Isotopes. Reactions with diphenylphosphine, metalations with  $\text{CoI}_2$  and  $\text{NiI}_2$ , and crystallizations were performed under dry, inert  $\text{N}_2$  atmosphere in a glovebox.

**Syntheses of the Ligands.** *N,N*-bis(2-hydroxyethyl)-4-methoxybenzylamine. Batches of 4-methoxybenzylamine (5.29 g, 38.5 mmol), 2-bromoethanol (10.6 g, 84.7 mmol) and excess triethylamine (20 mL) were dissolved together in 30 mL of toluene, and the mixture was allowed to reflux for 5 h. After cooling, the solvent was removed in vacuo, and tetrahydrofuran (THF) was added to the flask to dissolve the desired species. The flask was placed at  $-20^\circ\text{C}$  to precipitate the  $\text{NEt}_3 \cdot \text{HBr}$  completely. After filtration, the product was collected by evaporating the solvent. Yield: 6.94 g (80%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.30–6.83 (m, 4 H); 3.79 (s, 2 H, Ar– $\text{CH}_2\text{N}$ ); 3.61 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_2$ ); 2.69 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{OH})_2$ ); 2.49 (m, 2 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_2$ ).

*N,N*-bis(2-bromoethyl)-4-methoxybenzylamine. The bis-hydroxy starting material (4.00 g, 17.8 mmol) from the previous step was dissolved in 50 mL of  $\text{CH}_2\text{Cl}_2$ , and the solution was cooled to  $0^\circ\text{C}$  in an ice bath and brought under  $\text{N}_2$  atmosphere. To this stirred solution was added  $\text{PBr}_3$  (3.40 mL, 35.6 mmol) dropwise via syringe over the course of 20 min. During the next 2 h, the reaction temperature was maintained at  $0^\circ\text{C}$ , and a sticky yellow precipitate was observed. The reaction was allowed to come to room temperature over 2 h. Next, the reaction was quenched by addition of 10 mL of water at  $0^\circ\text{C}$ , and then neutralized to pH 7 with a saturated solution of  $\text{Na}_2\text{CO}_3$ . The organic layer was separated from the aqueous phase, dried over  $\text{MgSO}_4$ , and the solvent removed under reduced pressure. The product was purified via silica gel chromatography and eluted with  $\text{CH}_2\text{Cl}_2$ :hexanes (1:1) to afford a colorless oil. Yield: 4.40 g (71%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.26–6.82 (m, 4 H, Ar–H); 3.80 (s, 3 H, MeO); 3.65 (s, 2 H, Ar– $\text{CH}_2\text{N}$ ); 3.32 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{Br})_2$ ); 2.94 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{Br})_2$ ).

*N,N*-bis(2-(diphenylphosphino)ethyl)-4-methoxybenzylamine  $\{\text{MeOBzNP2}\}$ . Under  $\text{N}_2$  atmosphere in a glovebox, diphenylphosphine (0.880 g, 4.70 mmol) was diluted in 15 mL of THF and treated with 0.580 g (5.18 mmol) of  $t\text{BuOK}$ . The clear  $\text{Ph}_2\text{PH}$  solution turned to a bright red color upon addition of base, and the mixture was stirred at room temperature for 30 min. Separately, bis-bromo-4-methoxybenzylamine (0.790 g, 2.25 mmol) described above was dissolved in 5 mL of degassed THF. The deprotonated phosphine was brought to  $0^\circ\text{C}$ , and the solution of dibromo-species was added dropwise over the course of 10 min. After the addition was complete, the solution was colorless, and the reaction was allowed to come to ambient temperature over the next 5 h. Next, 5 mL of water were added to quench the reaction, and the THF was removed in vacuo; 30 mL of  $\text{CH}_2\text{Cl}_2$  were added and the organic layers collected and dried over  $\text{MgSO}_4$ , then the

solvent was removed under reduced pressure. The product was purified on silica gel using  $\text{CH}_2\text{Cl}_2$ /EtOAc/hexanes (1:10), and isolated as a white solid. Yield: 1.01 g (80%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.34–6.74 (m, 24 H, Ar-H); 3.79 (s, 3 H, MeO); 3.49 (s, 2 H, Ar- $\text{CH}_2$ -N); 2.59–2.51 (m, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{PPh}_2)_2$ ); 2.11–2.06 (m, 4 H,  $(\text{NCH}_2\text{CH}_2\text{PPh}_2)_2$ ).  $^{31}\text{P}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from  $\text{H}_3\text{PO}_4$ ):  $\delta$  -20.15 (s).  $^{13}\text{C}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  158.5 (s, 1 C), 138.5 (d, 4 C), 132.6 (d, 8 C), 131.1 (s, 1 C), 130.0 (s, 2 C), 128.5 (s, 4 C), 128.3 (d, 8 C), 113.6 (s, 2 C), 57.3 (s, 1 C), 55.3 (s, 1 C), 49.2 (d, 2 C), 25.4 (d, 2 C).

*N,N*-bis(2-hydroxyethyl)benzylamine. A large batch of benzyl bromide (7.14 g, 41.7 mmol) was dissolved in 30 mL of acetone. Separately, diethanolamine (4.82 g, 45.9 mmol) was dissolved in 5 mL of acetone and added to a stirred solution of the benzyl bromide, followed by addition of solid  $\text{Na}_2\text{CO}_3$  (4.42 g, 41.7 mmol). The solution was refluxed for 4 h and cooled to room temperature. Next, acetone was removed and 20 mL of water were added to dissolve the NaBr, followed by extraction with 30 mL of  $\text{CH}_2\text{Cl}_2$ . The organic layer was dried over  $\text{MgSO}_4$ , and the solvent evaporated to dryness. The resulting oil was washed with  $2 \times 10$  mL of hexane, affording the desired product as a clear oil. Yield: 6.76 g (83%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.33–7.29 (m, 5 H, Ar-H); 3.70 (s, 2 H, Ar- $\text{CH}_2$ -N); 3.61 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_2$ ); 2.71 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{OH})_2$ ); 2.44 (m, 2 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_2$ ).

*N,N*-bis(2-bromoethyl)benzylamine. The reaction of bis-hydroxy-4-benzylamine (5.65 g, 29.0 mmol) with 2 equiv of  $\text{PBr}_3$  (5.70 mL, 60.5 mmol) was performed as described above, and the crude product was isolated according to the same extraction procedure. The product was purified via silica gel chromatography and eluted with  $\text{CH}_2\text{Cl}_2$ :hexanes (1:2) to afford a colorless oil. Yield: 8.70 g (75%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.34–7.28 (m, 5 H, Ar-H); 3.73 (s, 2 H, Ar- $\text{CH}_2$ -N); 3.34 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{Br})_2$ ); 2.97 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{Br})_2$ ).

*N,N*-bis(2-(diphenylphosphino)ethyl)benzylamine  $\{\text{BzNP2}\}$ . The reaction of the bis-bromoethyl-benzylamine (2.25 g, 5.64 mmol) with 2.10 g of  $\text{Ph}_2\text{PH}$  (11.3 mmol) and 1.41 g of  $^t\text{BuOK}$  (12.4 mmol) in 30 mL of THF was carried out according to the procedure for  $\text{MeOBzNP2}$  as stated above. The product was purified on silica gel using  $\text{CH}_2\text{Cl}_2$  as solvent, and isolated as a white solid. Yield: 2.30 g (77%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.33–7.23 (m, 25 H, Ar-H); 3.56 (s, 2 H, Ar- $\text{CH}_2$ -N); 2.62–2.57 (m, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{PPh}_2)_2$ ); 2.13–2.08 (m, 4 H,  $(\text{NCH}_2\text{CH}_2\text{PPh}_2)_2$ ).  $^{31}\text{P}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from  $\text{H}_3\text{PO}_4$ ):  $\delta$  ppm -20.34 (s).  $^{13}\text{C}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  25.4 (d, 2 C), 49.3 (d, 2 C), 58.0 (s, 1 C), 126.9 (s, 1 C), 128.1–128.9 (m, 18 C), 132.6 (d, 8 C), 138.5 (d, 2 C), 139.1 (s, 1 C).

*N,N*-bis(2-hydroxyethyl)-4-bromobenzylamine. The reaction of 4-bromobenzylbromide (3.00 g, 12.0 mmol) with 1 equiv of diethanolamine and  $\text{Na}_2\text{CO}_3$  was carried out under the same conditions as described above. Yield: 2.73 g (83%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.46, 7.43 (d, 2 H, Ar-H); 7.28, 7.21 (d, 2 H, Ar-H); 3.65 (s, 2 H, Ar- $\text{CH}_2$ -N); 3.62 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_2$ ); 2.69 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{OH})_2$ ).

*N,N*-bis(2-bromoethyl)-4-bromobenzylamine. The reaction of bis-hydroxy-4-bromobenzylamine (1.50 g, 5.49 mmol) with 2 equiv of  $\text{PBr}_3$  (2.07 mL, 11.0 mmol) was performed as described above, and the crude product was isolated according to the same extraction procedure. The product was purified via silica gel chromatography and eluted with  $\text{CH}_2\text{Cl}_2$ :hexanes (1:2) to afford a colorless oil. Yield: 1.71 g (78%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.46, 7.44 (d, 2 H, Ar-H); 7.25, 7.22 (d, 2 H, Ar-H); 3.68 (s, 2 H, Ar- $\text{CH}_2$ -N); 3.34 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{Br})_2$ ); 2.95 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{Br})_2$ ).

*N,N*-bis(2-(diphenylphosphino)ethyl)-4-bromobenzylamine  $\{\text{BrBzNP2}\}$ . The reaction of the bis-bromoethyl-benzylamine (1.03 g, 2.58 mmol) with 0.960 g of  $\text{Ph}_2\text{PH}$  (5.15 mmol) and 0.640 g of  $^t\text{BuOK}$  (5.68 mmol) in

30 mL of THF was carried out, and the product purified as described above. Yield: 1.20 g (76%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.35–7.27 (m, 22 H, Ar-H); 7.09, 7.07 (d, 2 H, Ar-H); 3.48 (s, 2 H, Ar- $\text{CH}_2$ -N); 2.59–2.51 (m, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{PPh}_2)_2$ ); 2.12–2.09 (m, 4 H,  $(\text{NCH}_2\text{CH}_2\text{PPh}_2)_2$ ).  $^{31}\text{P}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from  $\text{H}_3\text{PO}_4$ ):  $\delta$  ppm -20.34 (s).  $^{13}\text{C}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  25.4 (d, 2 C), 49.3 (d, 2 C), 57.4 (s, 1 C), 120.6 (s, 1 C), 128.5 (m, 12 C), 130.5 (s, 2 C), 131.2 (s, 2 C), 132.6 (d, 8 C), 138.3 (m, 5 C).

*N,N*-bis(2-bromoethyl)phenylamine. The reaction of *N*-phenyl-diethanolamine (5.00 g, 27.6 mmol) with 2 equiv of  $\text{PBr}_3$  (5.40 mL, 55.2 mmol) was performed as described above, and the crude product was isolated according to the same extraction procedure. The product was purified via silica gel chromatography and eluted with  $\text{CH}_2\text{Cl}_2$ :hexanes (1:2) to afford a colorless oil. Yield: 6.60 g (78%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  6.67–7.30 (m, 5 H, Ar-H); 3.78 (t, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{Br})_2$ ); 3.46 (t, 4 H,  $(\text{NCH}_2\text{CH}_2\text{Br})_2$ ).

*N,N*-bis(2-(diphenylphosphino)ethyl)phenylamine  $\{\text{PhNP2}\}$ . The reaction of the bis-bromoethyl-phenylamine (1.69 g, 5.50 mmol) with 2.05 g of  $\text{Ph}_2\text{PH}$  (11.0 mmol) and 1.36 g of  $^t\text{BuOK}$  (12.1 mmol) in 30 mL of THF was carried out, and the product purified as described above. Yield: 2.13 g (75%).  $^1\text{H}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  7.43–6.33 (m, 25 H, Ar-H); 3.38–3.30 (m, 4 H,  $\text{N}(\text{CH}_2\text{CH}_2\text{PPh}_2)_2$ ); 2.30–2.25 (m, 4 H,  $(\text{NCH}_2\text{CH}_2\text{PPh}_2)_2$ ).  $^{31}\text{P}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from  $\text{H}_3\text{PO}_4$ ):  $\delta$  ppm -21.35 (s).  $^{13}\text{C}$  NMR in  $\text{CDCl}_3$  ( $\delta$  from TMS, in ppm):  $\delta$  25.9 (d, 2 C), 47.7 (d, 2 C), 112.3 (s, 2 C), 116.2 (s, 1 C), 128.6 (m, 12 C), 129.3 (s, 2 C), 132.7 (d, 8 C), 137.9 (d, 4 C), 146.7 (s, 1 C).

**Syntheses of the  $\text{Co}^{\text{II}}$  and  $\text{Ni}^{\text{II}}$  Complexes.** All  $\text{Co}^{\text{II}}$  and  $\text{Ni}^{\text{II}}$  complexes were prepared and recrystallized by procedures similar to those employed for  $[(\text{BzNP2})\text{Co}(\text{I})_2]$  (**Co-2**) and  $[(\text{BzNP2})\text{Ni}(\text{I})]\text{I}$  (**Ni-2**), as detailed below.

$[(\text{BzNP2})\text{Co}(\text{I})_2]$  (**Co-2**). The  $\text{BzNP2}$  ligand (0.200 g, 0.380 mmol) was dissolved in 10 mL of degassed THF. Separately, anhydrous  $\text{CoI}_2$  (0.118 g, 0.380 mmol) was slurried in 3 mL of THF and added dropwise to the stirred solution of the NP2 ligand at room temperature; this immediately generated a dark brown color. The solution was stirred for 12 h, and then filtered to remove a small amount of unreacted  $\text{CoI}_2$ . The brown solution was layered with 3 volumes of degassed hexane and after 3–4 days, orange-green crystals suitable for X-ray diffraction were obtained. Yield: 312 mg (90%). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in  $\text{M}^{-1} \text{cm}^{-1}$ ): 778 (220), 714 (300), 486 sh (440), 363 (1 900). Anal. Calcd. for  $\text{C}_{35}\text{H}_{35}\text{NP}_2\text{CoI}_2$ : C 49.79, H 4.18, N 1.66; found: C 50.45, H 4.02, N 1.92.

$[(\text{MeOBzNP2})\text{Co}(\text{I})_2]$  (**Co-1**). Reaction of the methoxy-appended  $\text{MeOBzNP2}$  ligand (0.20 g, 0.36 mmol) with 0.11 g of  $\text{CoI}_2$  (0.35 mmol) was performed as described above; the product crystallized from THF/hexane after several days. Yield: 277 mg (88%). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in  $\text{M}^{-1} \text{cm}^{-1}$ ): 778 (630), 715 (750), 487 sh (890), 363 (2 330). Anal. Calcd. for  $\text{C}_{36}\text{H}_{37}\text{NOP}_2\text{CoI}_2$ : C 49.45, H 4.27, N 1.60; found: C 48.83, H 4.77, N 1.45.

$[(\text{BrBzNP2})\text{Co}(\text{I})_2]$  (**Co-3**). Reaction of the bromine-appended  $\text{BrBzNP2}$  ligand (0.50 g, 0.82 mmol) with 0.26 g of  $\text{CoI}_2$  (0.82 mmol) was performed as described above; the product crystallized from THF/hexane after 1–2 days. Yield: 700 mg (93%). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in  $\text{M}^{-1} \text{cm}^{-1}$ ): 778 (790), 718 (910), 486 sh (990), 363 (2 630). Anal. Calcd. for  $\text{C}_{35}\text{H}_{34}\text{NBrP}_2\text{CoI}_2$ : C 45.53, H 3.71, N 1.52; found: C 44.93, H 3.76, N 1.71.

$[(\text{PhNP2})\text{Co}(\text{I})_2]$  (**Co-4**). Reaction of  $\text{PhNP2}$  ligand (0.15 g, 0.29 mmol) with 0.09 g of  $\text{CoI}_2$  (0.29 mmol) was performed as described above; the product crystallized from THF/hexane after 1–2 days. Yield: 220 mg (90%). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in  $\text{M}^{-1} \text{cm}^{-1}$ ): 363 (950). Anal. Calcd. for  $\text{C}_{34}\text{H}_{33}\text{NP}_2\text{CoI}_2$ : C 49.18, H 4.01, N 1.69; found: C 49.28, H 3.82, N 1.49.

$[(\text{P}(\text{N}_{\text{Ph}})\text{P})\text{Co}(\text{I})_2]$  (**Co-PNP**). Reaction of the PNP type of ligand  $\text{P}(\text{N}_{\text{Ph}})\text{P}$  (0.30 g, 0.61 mmol) with 0.19 g of  $\text{CoI}_2$  (0.61 mmol) was



Table 1. Crystal Data and Refinement Parameters for NP2-Co<sup>II</sup> Complexes

	Co-1	Co-2	Co-3	Co-4
empirical formula	C <sub>36</sub> H <sub>37</sub> NOP <sub>2</sub> CoI <sub>2</sub>	C <sub>35</sub> H <sub>35</sub> NP <sub>2</sub> CoI <sub>2</sub> · C <sub>4</sub> H <sub>8</sub> O	C <sub>35</sub> H <sub>34</sub> NP <sub>2</sub> BrCoI <sub>2</sub>	C <sub>34</sub> H <sub>33</sub> NP <sub>2</sub> CoI <sub>2</sub>
FW	874.34	916.41	923.21	830.28
color	green	green	green	dark green
habit	needle	blade	plate	block
size (mm)	0.38 × 0.10 × 0.07	0.20 × 0.10 × 0.07	0.19 × 0.14 × 0.07	0.31 × 0.23 × 0.11
T (K)	100(2)	100(2)	100(2)	100(2)
wavelength (Å)	0.71073	0.71073	0.71073	0.71073
lattice system	orthorhombic	monoclinic	triclinic	orthorhombic
space group	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>	P2 <sub>1</sub> /c	P $\bar{1}$	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>
a (Å)	9.2880(4)	9.1301(5)	9.5306(4)	11.7095(6)
b (Å)	13.5281(5)	14.38705(7)	11.7513(5)	14.2950(7)
c (Å)	27.2546(11)	28.7247(14)	15.7593(7)	19.3910(11)
$\alpha$ (deg)	90	90	98.758(2)	90
$\beta$ (deg)	90	94.000(2)	93.890(2)	90
$\gamma$ (deg)	90	90	101.072(2)	90
V (Å <sup>3</sup> )	3424.5(2)	3763.9(3)	1703.35(13)	3237.6(3)
Z	4	4	2	4
$d_{\text{calc}}$ (g/cm <sup>3</sup> )	1.696	1.617	1.800	1.703
$\mu$ (mm <sup>-1</sup> )	2.427	2.212	3.609	2.560
GOF on F <sup>2</sup>	1.548	1.663	1.433	1.268
final R indices	R1 = 0.0241	R1 = 0.0287	R1 = 0.0280	R1 = 0.0224
[I > 2 $\sigma$ (I)]	wR2 = 0.0376	wR2 = 0.0411	wR2 = 0.0381	wR2 = 0.0316
R indices	R1 = 0.0283	R1 = 0.0427	R1 = 0.0445	R1 = 0.0306
all data	wR2 = 0.0381	wR2 = 0.0424	wR2 = 0.0393	wR2 = 0.0326

performed as described above; the product crystallized from THF/hexane after 3–4 days. Yield: 400 mg (82%). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in M<sup>-1</sup> cm<sup>-1</sup>): 781 (630), 718 (790), 487 (1 170), 363 sh (3 170). Anal. Calcd. for C<sub>32</sub>H<sub>29</sub>NP<sub>2</sub>CoI<sub>2</sub>: C 47.91, H 3.64, N 1.75; found: C 47.58, H 3.79, N 1.77.

[(Br<sub>2</sub>NP<sub>2</sub>)Ni(I)] (Ni-2). The Br<sub>2</sub>NP<sub>2</sub> ligand (0.15 g, 0.28 mmol) was dissolved in 5 mL of degassed THF. Separately, anhydrous NiI<sub>2</sub> (0.088 g, 0.28 mmol) was dissolved in 5 mL of THF by vigorously stirring and then added dropwise to the stirred solution of the NP<sub>2</sub> ligand at room temperature; this immediately generated a red-violet color. The solution was stirred for 12 h, and then filtered to remove the unreacted NiI<sub>2</sub>. The red-violet solution was layered with 3 volumes of degassed hexane and after 3–4 days, red crystals suitable for X-ray diffraction were obtained. Yield: 210 mg (89%). <sup>1</sup>H NMR in CDCl<sub>3</sub> ( $\delta$  from TMS, in ppm):  $\delta$  8.48–8.46 (m, 2 H, Ar-H); 7.86–7.42 (m, 23 H, Ar-H); 4.41 (s, 2 H, Ar-CH<sub>2</sub>-N); 3.96 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 3.26–3.21 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.98–2.94 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.71–2.64 (m, 2 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>). <sup>31</sup>P NMR in CDCl<sub>3</sub> ( $\delta$  from H<sub>3</sub>PO<sub>4</sub>):  $\delta$  ppm 35.65 (s). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in M<sup>-1</sup> cm<sup>-1</sup>): 341 sh (4 230), 294 sh (8 780). Anal. Calcd. for C<sub>35</sub>H<sub>35</sub>NP<sub>2</sub>NiI<sub>2</sub>: C 49.80, H 4.18, N 1.66; found: C 49.97, H 3.99, N 1.80.

[(MeOBr<sub>2</sub>NP<sub>2</sub>)Ni(I)] (Ni-1). Reaction of the methoxy-appended MeOBr<sub>2</sub>NP<sub>2</sub> ligand (83 mg, 0.15 mmol) with 46 mg of NiI<sub>2</sub> (0.15 mmol) was performed as described above; the product crystallized from THF/hexane after 3–4 days. Yield: 110 mg (83%). <sup>1</sup>H NMR in CDCl<sub>3</sub> ( $\delta$  from TMS, in ppm):  $\delta$  8.36, 8.33 (d, 2 H, Ar-H); 7.82–7.44 (m, 20 H, Ar-H); 6.92, 6.90 (d, 2 H, Ar-H); 4.34 (s, 2 H, Ar-CH<sub>2</sub>-N); 3.90 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 3.81 (s, 3 H, MeO); 3.17 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.92 (m, 2 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.74–2.67 (m, 2 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>). <sup>31</sup>P NMR in CDCl<sub>3</sub> ( $\delta$  from H<sub>3</sub>PO<sub>4</sub>):  $\delta$  ppm 35.47 (s). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in M<sup>-1</sup> cm<sup>-1</sup>):

337 sh (3 310), 294 sh (6 630). Anal. Calcd. for C<sub>36</sub>H<sub>37</sub>NOP<sub>2</sub>NiI<sub>2</sub>: C 49.46, H 4.27, N 1.60; found: C 49.05, H 4.15, N 1.48.

[(Br<sub>2</sub>NP<sub>2</sub>)Ni(I)] (Ni-3). Reaction of the bromine-appended Br<sub>2</sub>NP<sub>2</sub> ligand (0.20 g, 0.33 mmol) with 0.11 g of NiI<sub>2</sub> (0.33 mmol) was performed as described above; the product crystallized from THF/hexane after 1–2 days. Yield: 270 mg (88%). <sup>1</sup>H NMR in CDCl<sub>3</sub> ( $\delta$  from TMS, in ppm):  $\delta$  8.74, 8.44 (d, 2 H, Ar-H); 7.82–7.43 (m, 22 H, Ar-H); 4.41 (s, 2 H, Ar-CH<sub>2</sub>-N); 4.04 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 3.22 (m, 2 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.91–2.74 (m, 2 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.70–2.17 (m, 2 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>). <sup>31</sup>P NMR in CDCl<sub>3</sub> ( $\delta$  from H<sub>3</sub>PO<sub>4</sub>):  $\delta$  ppm 35.46 (s). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in M<sup>-1</sup> cm<sup>-1</sup>): 338 sh (2 660), 294 sh (7 140). Anal. Calcd. for C<sub>35</sub>H<sub>34</sub>NBrP<sub>2</sub>NiI<sub>2</sub>: C 45.54, H 3.71, N 1.52; found: C 45.30, H 3.83, N 1.40.

[(P<sub>h</sub>NP<sub>2</sub>)Ni(I)] (Ni-4). Reaction of the P<sub>h</sub>NP<sub>2</sub> ligand (190 mg, 0.36 mmol) with 120 mg of NiI<sub>2</sub> (0.37 mmol) was performed as described above; the product crystallized from THF/hexane after several days. Yield: 260 mg (85%). <sup>1</sup>H NMR in CDCl<sub>3</sub> ( $\delta$  from TMS, in ppm):  $\delta$  8.09, 8.07 (d, 2 H, Ar-H); 7.64–7.43 (m, 23 H, Ar-H); 4.62 (m, 3 H, N(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 3.46 (m, 3 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>); 2.68–2.64 (m, 2 H, (NCH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>2</sub>). <sup>31</sup>P NMR in CDCl<sub>3</sub> ( $\delta$  from H<sub>3</sub>PO<sub>4</sub>):  $\delta$  ppm 36.06 (s). UV/vis in THF,  $\lambda$  in nm ( $\epsilon$  in M<sup>-1</sup> cm<sup>-1</sup>): 360 (1 610), 294 (3 720). Anal. Calcd. for C<sub>34</sub>H<sub>33</sub>NP<sub>2</sub>NiI<sub>2</sub>: C 49.20, H 4.01, N 1.69; found: C 48.66, H 4.12, N 1.52.

[(P(N<sub>Ph</sub>)P)Ni(I)] (Ni-PNP). Reaction of the P<sup>h</sup>P(N<sub>Ph</sub>)P<sup>h</sup> ligand (0.30 g, 0.61 mmol) with 0.19 g of NiI<sub>2</sub> (0.61 mmol) was performed as described above. Yield: 410 mg (84%). <sup>1</sup>H NMR in CDCl<sub>3</sub> ( $\delta$  from TMS, in ppm):  $\delta$  ppm, 9.25 (br m, 2 H); 7.37 (br d, 9 H); 7.06 (br m, 8 H); 6.82 (br m, 2 H); 6.13 (br m, 4 H); 4.68 (br s, 4 H). <sup>31</sup>P NMR in CDCl<sub>3</sub> ( $\delta$  from H<sub>3</sub>PO<sub>4</sub>):  $\delta$  ppm -5.11 (s). Anal. Calcd. for C<sub>32</sub>H<sub>29</sub>NP<sub>2</sub>NiI<sub>2</sub>: C 47.92, H 3.64, N 1.75; found: C 48.36, H 3.61, N 1.97.

Table 2. Selected Bond Distances (Å) and Bond Angles (deg) from Crystal Structures of the Cobalt Complexes<sup>a</sup>

	Co-1	Co-2 (P <sub>2</sub> /c)	Co-2 (DFT)	Co-2'	Co-3	Co-3 (DFT)	Co-4
Co–P1	2.3529(3)	2.3563(4)	2.339	2.1945(5)	2.3761(3)	2.310 <sup>b</sup>	2.3511(3)
Co–P2	2.3572(3)	2.3566(4)	2.333	2.2228(5)	2.3990(3)	2.354 <sup>b</sup>	2.3420(3)
Co–I1	2.57678(19)	2.5703(2)	2.569	2.6023(3)	2.5766(17)	2.566	2.58189(16)
Co–I2	2.54416(17)	2.5599(2)	2.583	2.7480(4)	2.5650(17)	2.585	2.54249(15)
Co–N	3.690	3.674	3.658	2.0769(18)	3.675	3.633	3.684
P1–Co–P2	113.307(11)	114.376(14)	114.68	161.57(2)	115.373(10)	115.65	113.829(9)
P–Co–I (avg)	107.284(9)	106.696(12)	107.12	95.994(16)	106.594(8)	106.57	106.651(8)
I1–Co–I2	114.400(6)	115.503(8)	115.40	95.229(12)	115.006(6)	114.96	116.386(5)

<sup>a</sup> Also included for comparison are DFT-optimized (6-31G\*<sup>b</sup>/PW91) bond distances for Co-2 and Co-3. <sup>b</sup> Denotes a difference of greater than 0.05 Å.

Table 3. Crystal Data and Refinement Parameters for the NP2-Ni<sup>II</sup> Complexes

	Ni-1	Ni-2	Ni-3	Ni-4
empirical formula	[C <sub>36</sub> H <sub>37</sub> NOP <sub>2</sub> INi] <sup>+</sup> I <sup>−</sup>	[C <sub>35</sub> H <sub>35</sub> INP <sub>2</sub> Ni] <sup>+</sup> I <sup>−</sup> · CH <sub>2</sub> Cl <sub>2</sub>	[C <sub>35</sub> H <sub>34</sub> NP <sub>2</sub> BrINi] <sup>+</sup> I <sup>−</sup>	[C <sub>34</sub> H <sub>33</sub> NP <sub>2</sub> INi] <sup>+</sup> I <sup>−</sup> · C <sub>4</sub> H <sub>8</sub> O
FW	874.12	929.02	922.99	902.17
color	purple	deep purple	dark purple	red
habit	block	blade	block	block
size (mm)	0.28 × 0.27 × 0.18	0.20 × 0.18 × 0.10	0.21 × 0.18 × 0.15	0.29 × 0.28 × 0.15
T (K)	100(2)	100(2)	100(2)	100(2)
wavelength (Å)	0.71073	0.71073	0.71073	0.71073
lattice system	triclinic	monoclinic	triclinic	triclinic
space group	P $\bar{1}$	P <sub>2</sub> /n	P $\bar{1}$	P $\bar{1}$
a (Å)	11.9939(5)	8.9712(4)	11.9678(6)	9.7033(3)
b (Å)	12.7222(5)	24.7251(10)	12.1991(12)	12.3287(4)
c (Å)	12.9714(9)	16.2706(7)	13.2965(7)	15.5781(5)
α (deg)	105.152(2)	90	103.056(4)	86.4940(10)
β (deg)	100.967(2)	93.804(2)	108.995(3)	87.5220(10)
γ (deg)	110.363(2)	90	102.700(4)	89.1920(10)
V (Å <sup>3</sup> )	1702.42(15)	3601.1(3)	1695.0(2)	1858.24(10)
Z	2	4	2	2
d <sub>calc</sub> (g/cm <sup>3</sup> )	1.705	1.714	1.808	1.612
μ (mm <sup>−1</sup> )	2.507	2.517	3.693	2.299
GOF on F <sup>2</sup>	2.336	1.675	2.002	2.081
final R indices	R1 = 0.0282	R1 = 0.0299	R1 = 0.0329	R1 = 0.0282
[I > 2σ(I)]	wR2 = 0.0497	wR2 = 0.0414	wR2 = 0.0520	wR2 = 0.0586
R indices	R1 = 0.0400	R1 = 0.0459	R1 = 0.0475	R1 = 0.0348
all data	wR2 = 0.0502	wR2 = 0.0426	wR2 = 0.0529	wR2 = 0.0601

**X-ray Crystallography.** Crystals were mounted on a glass fiber using Paratone oil, and then placed on the diffractometer under a stream of N<sub>2</sub> at 100 K. Refinement of F<sup>2</sup> against all reflections: the weighted R-factor (wR) and goodness of fit (S) were based on F<sup>2</sup>, conventional R-factors (R) were based on F, with F set to zero for negative F<sup>2</sup>. The threshold expression F<sup>2</sup> > 2σ(F<sup>2</sup>) was used only for calculating R-factors(gt) and was not relevant to the choice of reflections for refinement. Diffraction intensity data were collected on a Bruker Kappa APEX II diffractometer equipped with a MoKα X-ray source, and data were collected using APEX2 v2009.7–0; the data reduction program SAINT-plus v7.66A was used. Details of the data collections and refinements are given in Tables 1 and 3.

**Magnetism.** Magnetic susceptibilities for Co-1, Co-2, Co-3, and Co-4 were recorded at 5000 G using a Quantum Designs SQUID magnetometer controlled by MPMSR2 software. Data points acquired from 4 to 300 K were corrected for diamagnetic contributions (Pascal's constants).<sup>19</sup> The output was converted to effective magnetic moment (μ<sub>eff</sub>) and plotted as BM (μ<sub>B</sub>) versus temperature (K).

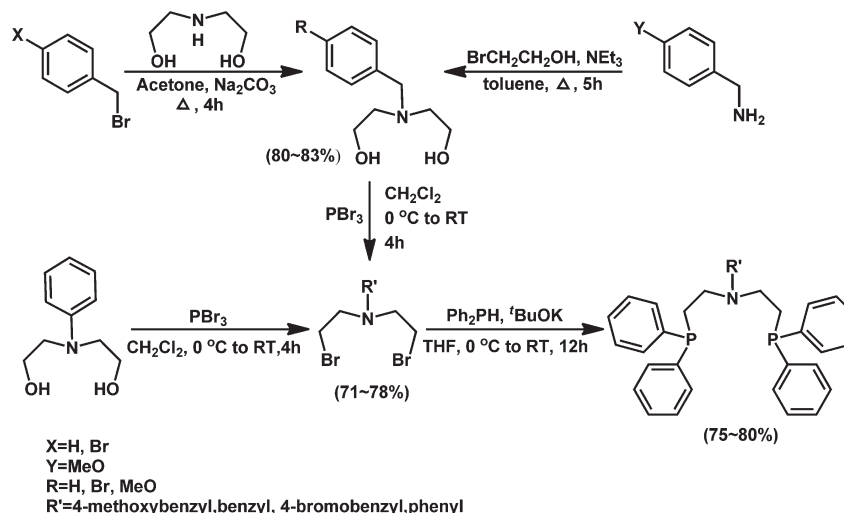
**Spectroscopy.** The <sup>1</sup>H, <sup>13</sup>C, and <sup>31</sup>P NMR spectra were recorded on a Varian Mercury 300 MHz spectrometer, and chemical shifts were referenced to TMS (<sup>1</sup>H, <sup>13</sup>C) or H<sub>3</sub>PO<sub>4</sub> (<sup>31</sup>P). EPR spectra were recorded on a Bruker EMX Biospin spectrometer at 20 K using a Gunn diode microwave source. UV/vis spectra were obtained at 298 K using a Cary 50 spectrophotometer.

**Density Functional Theory (DFT) Calculations.** Geometry optimization on the crystal structure coordinates as well as orbital calculations were performed using the pure functional PW91<sup>20</sup> and the 6-31G\* basis set (6-311G\* for iodine) in the Firefly software package.<sup>21</sup> Orbitals were visualized using MacMolPlt,<sup>22</sup> and spin density plots were generated using gOpenMol.<sup>23</sup>

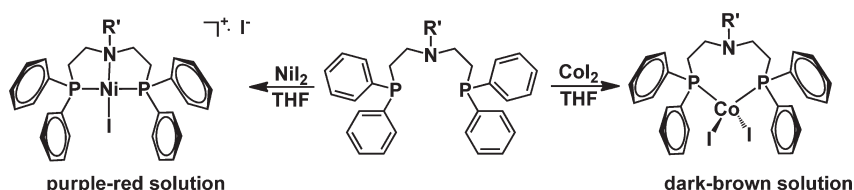
## RESULTS AND DISCUSSION

**Syntheses.** We have synthesized a series of NP2 ligands with a flexible {P-CH<sub>2</sub>CH<sub>2</sub>-N-CH<sub>2</sub>CH<sub>2</sub>-P} binding unit.

Scheme 3



Scheme 4

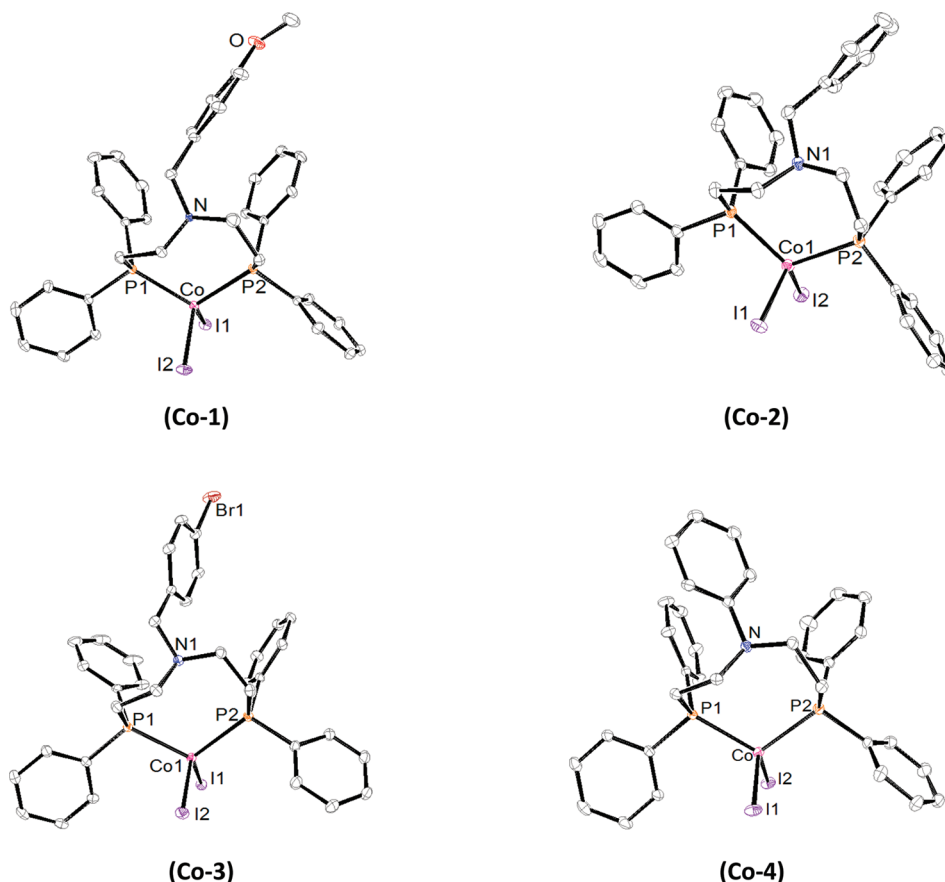


Many reported PNP compounds were synthesized via a Manich-type reaction with the corresponding phosphine, amines, and  $\text{CH}_2\text{O}$ , thereby providing methylene linked ligands. We opted for a different approach to prepare ethylene-bridged ligands. Our first targeted compound was the bis-hydroxyethyl derivative. Reaction of benzylbromide (or 4-bromobenzylbromide) with diethanolamine in acetone ( $\text{Na}_2\text{CO}_3$  as base) afforded the corresponding bis-hydroxyethyl derivatives in excellent yields. Alternatively, the  $-\text{OMe}$  appended bis-hydroxyethyl derivative was produced by refluxing a mixture of 4-methoxybenzylamine, 2-bromoethanol, and  $\text{NEt}_3$  in toluene for 5 h; *N*-phenyldiethanolamine is commercially available. Subsequent activation of the alcohols with  $\text{PBr}_3$  generated the brominated derivatives (71–78%), which upon disubstitution with diphenylphosphine ( $t\text{BuOK}$  as base) afforded the NP2 ligands as air-stable, white solids in very good yield (75–80%, Scheme 3).

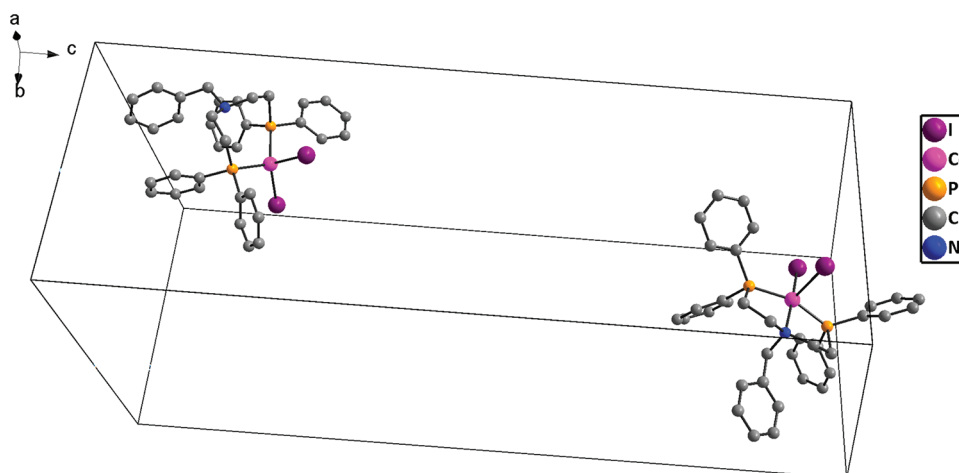
Metalation of 1 equiv of a given NP2 ligand with anhydrous  $\text{CoI}_2$  in THF at room temperature afforded a dark brown solution (Scheme 4). Crystals of the resulting  $\text{Co}^{\text{II}}$  complexes of general formula  $[(\text{RNP2})\text{Co}(\text{I})_2]$  were isolated in nearly quantitative yield (81–92%). The  $\text{Ni}^{\text{II}}$  species also were prepared by the reaction of 1 equiv of the NP2 ligands with anhydrous  $\text{NiI}_2$  in THF under inert atmosphere. The resulting violet solutions generated copious amounts of purple solid that could be recrystallized from THF/hexane. X-ray crystallography (see below) identified these complexes as the cationic species of general formula  $[(\text{RNP2})\text{Ni}(\text{I})]^+$  in very good yield (82–90%). The  $\text{Ni}^{\text{II}}$  complexes exhibit sharp  $^1\text{H}$  and  $^{31}\text{P}$  NMR spectra in the diamagnetic region, consistent with an  $S = 0$  ground state.

**Crystal Structures of the Cobalt Complexes.** The  $\text{Co}^{\text{II}}$  center in each of the complexes of general formula  $[(\text{RNP2})\text{Co}(\text{I})_2]$  is coordinated by two phosphino-P donors provided by bidentate NP2 as well as two iodide ions, adopting a tetrahedral geometry (Figure 1; selected bond lengths and bond angles are in Table 2.) Crystal data and refinement parameters for NP2- $\text{Co}^{\text{II}}$  complexes are collected in Table 1. The overall structures of these four-coordinate  $\text{Co}^{\text{II}}$  complexes are pseudotetrahedral with  $\text{P1}-\text{Co}-\text{P2}$  ( $113.307^\circ - 115.373^\circ$ ),  $\text{P}-\text{Co}-\text{I}$  (avg) ( $106.594^\circ - 107.284^\circ$ ) and  $\text{I1}-\text{Co}-\text{I2}$  ( $114.400^\circ - 116.386^\circ$ ) bond angles that deviate only slightly from ideal values. The  $\text{Co}-\text{P}$  bond lengths ( $2.3511(3) - 2.3761(3)$  Å) are longer than those observed in complexes bearing a bidentate P2N2 ligand, such as  $[(\text{P}^{\text{Ph}}_2\text{N}^{\text{Ph}}_2)\text{Co}(\text{MeCN})_3]^{2+}$  ( $2.198(5)$  Å) or  $[(\text{P}^{\text{Ph}}_2\text{N}^{\text{Ph}}_2)_2\text{Co}(\text{Cl})]^+$  ( $2.2133(8)$  and  $2.2368(8)$  Å).<sup>15</sup> They also are longer than those in  $[(\text{PhBP3})-\text{Co}(\text{I})]$  ( $\text{BP3}^- = \text{PhB}(\text{CH}_2\text{P}(\text{Ph})_2)_3^-$ ) ( $2.200(2)$ ,  $2.206(2)$ , and  $2.282(2)$  Å).<sup>24</sup> The  $\text{Co}-\text{I}$  bond lengths (avg  $\text{Co}-\text{I} = 2.565$  Å) are longer than those observed in  $[(\text{PhBP3})\text{Co}(\text{I})]$  ( $2.488(1)$  Å) and  $[(\text{PhBP}^{\text{Pr}}_3)\text{Co}(\text{I})]$  ( $2.540(1)$  Å), which may be attributable to the different number of coordinated iodides in each case. The distances between the  $\text{Co}^{\text{II}}$  center and the unbound N donor lie in the narrow range  $3.674 - 3.690$  Å.

The related P2N2 and PNP ligands are methylene linked. In a P-N-P bonded chelate, these ligands would generate two unfavorable 4-membered rings among the  $\{\text{Co}-\text{P}-\text{CH}_2-\text{N}-(\text{Co})\}$  atoms. The NP2 ligands, with an ethylene linker between the phosphorus and nitrogen atoms, could form two ideal  $\{\text{Co}-\text{P}-\text{CH}_2-\text{CH}_2-\text{N}-(\text{Co})\}$  5-membered rings; in most cases (vide infra) the nitrogen remains unbound, indicating that the tetrahedral cobalt center prefers phosphorus ligation.



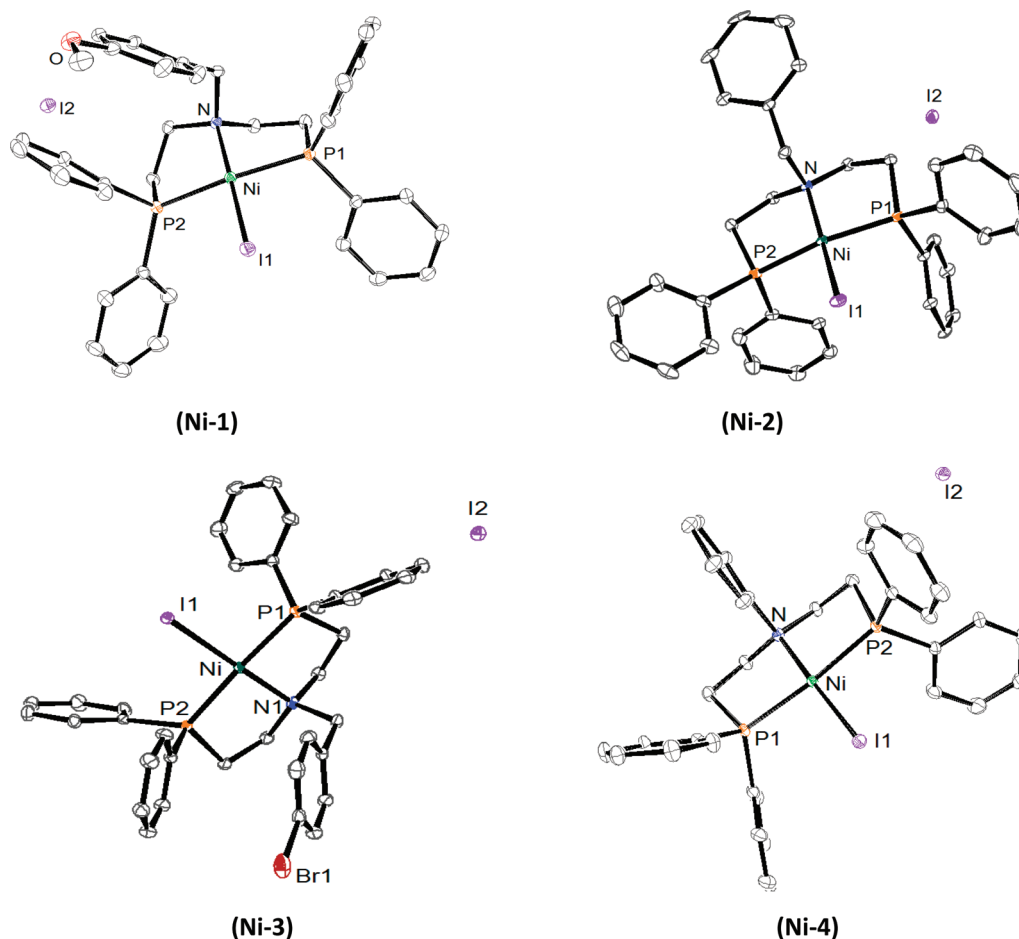
**Figure 1.** ORTEP diagrams (50% thermal ellipsoids):  $[(\text{MeO}_{\text{Bz}}\text{NP2})\text{Co}(\text{I})_2]$  (**Co-1**);  $[(\text{BzNP2})\text{Co}(\text{I})_2]$  (**Co-2**);  $[(\text{Br}_{\text{Bz}}\text{NP2})\text{Co}(\text{I})_2]$  (**Co-3**);  $[(\text{PhNP2})\text{Co}(\text{I})_2]$  (**Co-4**).



**Figure 2.** Ball and stick diagram of the asymmetric part of the unit cell ( $Cc$  crystal structure) containing  $[(\text{BzNP2})\text{Co}(\text{I})_2]$  structural conformers: **Co-2**, tetrahedral (left side); **Co-2'**, square pyramidal (right side).

One notable exception is the five-coordinate  $\text{Co}^{\text{II}}$  complex obtained from the reaction of  $\text{CoI}_2$  with 2 equiv of  $\text{BzNP2}$ . In this case, the complex crystallized in a different space group ( $Cc$ ), in contrast to the crystal structure that contains only the tetrahedral complex described above ( $P2_1/c$ ). Figure 2 displays the asymmetric part of the  $Cc$  unit cell, which contains two structural conformers denoted **Co-2** (tetrahedral) and **Co-2'** (square

pyramidal). In the case of **Co-2'** (right side), the cobalt center adopts a square pyramidal geometry because of binding of the benzylamino- $N$  donor. The  $\text{I}^-$  occupies the apical position, while the other  $\text{I}^-$ , two phosphorus atoms and nitrogen reside in the basal plane. The  $\text{Co}-\text{N}$  bond length (2.0769(18) Å) is much shorter than  $\{\text{Co}-\text{N}\}$  in the tetrahedral  $\text{Co}$  complexes ( $\sim 3.7$  Å), but slightly longer than the  $\text{Co}-\text{N}_{\text{MeCN}}$  bond lengths



**Figure 3.** ORTEP diagrams (50% thermal ellipsoids):  $[(\text{MeO}_{\text{Bz}}\text{NP2})\text{Ni}(\text{I})]\text{I}$  (Ni-1);  $[(\text{Bz}\text{NP2})\text{Ni}(\text{I})]\text{I}$  (Ni-2);  $[(\text{Br}_{\text{Bz}}\text{NP2})\text{Ni}(\text{I})]\text{I}$  (Ni-3);  $[(\text{Ph}\text{NP2})\text{Ni}(\text{I})]\text{I}$  (Ni-4).

**Table 4.** Selected Bond Distances (Å) and Bond Angles (deg) from Crystal Structures of  $\text{Ni}^{\text{II}}$  Complexes

	Ni-1	Ni-2	Ni-3	Ni-4	Ni-PNP
Ni–P1	2.2139(2)	2.2039(3)	2.2062(4)	2.2264(4)	2.1833(3)
Ni–P2	2.1916(2)	2.2319(3)	2.2039(4)	2.2181(4)	2.1760(3)
Ni–I1	2.4739(2)	2.4744(16)	2.4871(3)	2.4870(2)	2.53658(15)
Ni–I2					2.53083(14)
Ni–N	2.0051(7)	1.9864(8)	1.9887(11)	1.9911(12)	3.771
P1–Ni–P2	164.876(10)	157.662(13)	175.916(15)	173.670(16)	93.381(10)
P1–Ni–I1	94.251(7)	92.936(8)	91.784(11)	94.559(11)	176.719(9)
P1–Ni–I2					174.479(9)
N–Ni–I1	177.22(2)	166.37(3)	174.92(3)	178.26(3)	

in  $[\text{Co}(\text{P}^{\text{Ph}}_2\text{N}^{\text{Ph}}_2)(\text{CH}_3\text{CN})_3](\text{BF}_4)_2$  (1.952, 2.078, 1.943 Å)<sup>15</sup> or  $[\text{Co}(\text{P}^{\text{tBu}}_2\text{N}^{\text{Bz}}_2)(\text{CH}_3\text{CN})_3](\text{BF}_4)_2$  (1.961, 1.955, 2.059 Å).<sup>14</sup> The Co–P distances are both shortened (2.1945(5) and 2.2228(5) Å) once the N-donor is bound. On the other hand, the Co–I bond lengths are elongated (2.6023(3) and 2.7480(4) Å). The structure of the Cc tetrahedral Co-2 is nearly identical with that in the  $P2_1/c$  crystal.

**Crystal Structures of the Nickel Complexes.** Table 3 shows crystal data and refinement parameters for the  $\text{NP2-Ni}^{\text{II}}$  complexes. ORTEP diagrams for the four square planar  $\text{rNP2-Ni}^{\text{II}}$  complexes are shown in Figure 3; selected bond angles and bond

distances are in Table 4. The N-donor in  $\text{rNP2}$  is bound to  $\text{Ni}^{\text{II}}$ , even in the case of  $\text{PhNP2}$  (Ni-4). In each case, one  $\text{I}^-$  ligand occupies the fourth coordination site, while the other  $\text{I}^-$  is an outer coordination counterion. Ni-1, Ni-3, and Ni-4 exhibit P1–Ni–P2 and N–Ni–I1 angles in the range 164.876(10)–178.26(3)°; Ni-2 exhibits a more distorted square planar geometry, with P1–Ni–P2 and N–Ni–I1 angles of 157.662(13)° and 166.37(3)°, respectively. The dihedral angle P1–Ni–I1/P2–Ni–N in Ni-2 is 24.95°. The Ni–P bonds (2.2039(3) and 2.2319(3) Å) in Ni-2 are elongated by comparison to the other distorted Ni complexes. The Ni–P bond lengths (Ni-1 = 2.203, Ni-2 = 2.221, Ni-3 = 2.205, Ni-4 = 2.222 Å) are very close to those in  $[(\text{PNP})\text{Ni}(\text{dmpm})](\text{BF}_4)_2$  ( $\text{Ni–P}_{\text{avg}} \approx 2.21$  Å).<sup>25</sup>

ORTEP diagrams for Ni-PNP and Co-PNP complexes are shown in Figure 4 (for crystal data and refinement parameters see Supporting Information, Table S1). In contrast to Ni-1 to Ni-4, only P-donors are coordinated in Ni-PNP, as the aniline N-donor is approximately 3.8 Å away from the metal center. The Ni–P bonds in Ni-PNP (Ni–P1 = 2.1833(3), Ni–P2 = 2.1760(3) Å) are shorter than the average Ni–P length in Ni-1–Ni-4 (Ni–P1 = 2.2126(3), Ni–P2 = 2.2114(3) Å), most likely because of the “pinched” geometry in the methylene-linked PNP. As a result, the Ni–I1 bond lengths in Ni-PNP (2.53658(15) Å) are longer than the average Ni–I1 distance in Ni-1–Ni-4 (2.4806(6) Å), likely attributable to a stronger *trans* effect of the more closely bonded P-donors. We suggest that



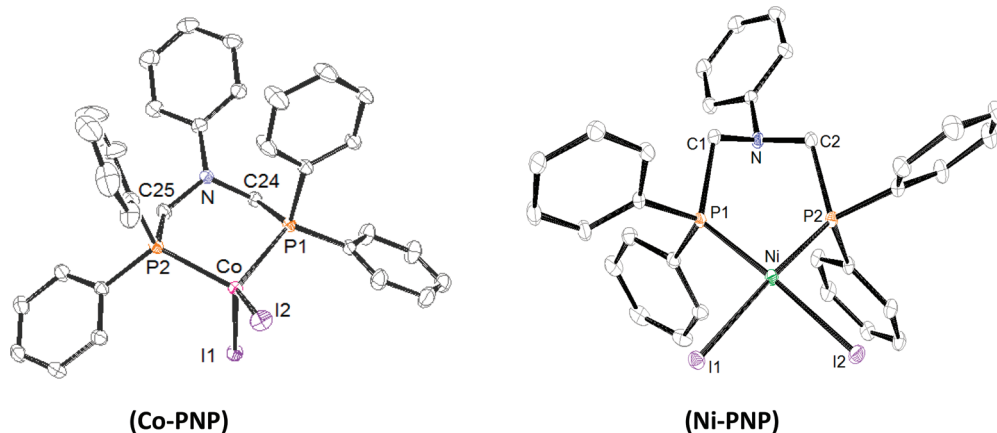


Figure 4. ORTEP diagrams (50% thermal ellipsoids):  $[(P(N_{Ph})P)Co(I)_2]$  (Co-PNP);  $[(P(N_{Ph})P)Ni(I)_2]$  (Ni-PNP).

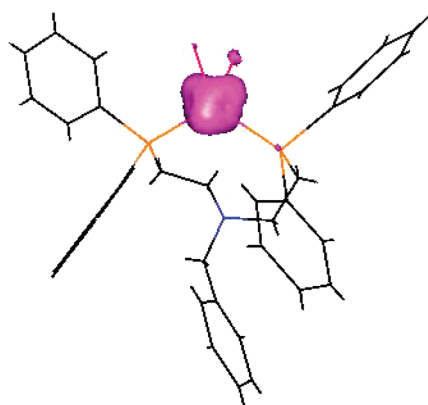


Figure 5. DFT (6-31G\*/PW91) spin density plot for the  $S = 3/2$  ground state of the geometry optimized Co-2 structure.

the nitrogen atom of the NP2 ligand acts as a “claw” to pull  $Ni^{II}$  back, thus forming two 5-membered rings when the nitrogen is bound to the metal center. The corresponding  $Co^{II}$  structure is unremarkable, as Co-PNP exhibits a similar P-only coordination mode as in Ni-PNP and Co-1–Co-4. Thus, the dual coordination modes of ethylene-linked  $RNP2$  ligands are not observed in P-only complexes containing PNP.

**DFT Calculations.** We performed DFT calculations on Co-2 and Co-3 as model compounds. Geometry optimization at the 6-31G\*/PW91 ( $S = 3/2$ ) level afforded bond distances and bond angles very similar to those found in the crystal structure, with no differences in bond lengths  $>0.03$  Å (Table 2). DFT calculations on Co-3 gave similar results, although the Co–P bonds in the calculation (2.310, 2.354 Å) were significantly shorter than those in the crystal (2.3761(3), 2.3990(3) Å); the Co–I bonds, however, were in good agreement (diff  $<0.02$  Å). In the DFT calculation, the  $S = 3/2$  ground state of Co-2 is approximately 25 kcal/mol more stable than the  $S = 1/2$  state, as observed in some tetrahedral  $Co^{II}$  complexes bearing anionic phosphine ligands.<sup>24</sup> The spin density of Co-2 (shown in Figure 5) is consistent with that expected for a nearly ideal  $T_d$  system, a result in accord with SQUID data (vide infra). It was necessary to establish unambiguously the  $S = 3/2$  ground state in the solid state by SQUID and DFT calculations in light of unexpected EPR results (vide infra).

**Magnetic Susceptibilities.** We determined magnetic susceptibilities for Co-1, Co-2, Co-3, and Co-4 over the temperature

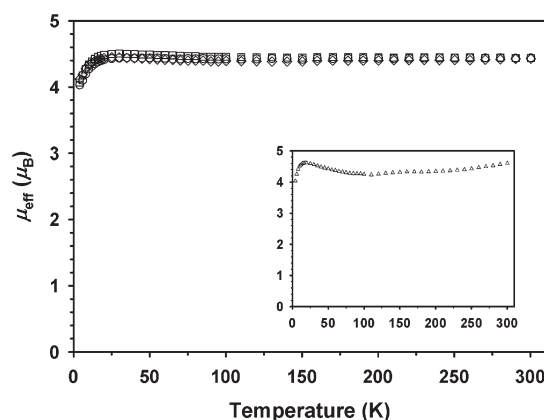
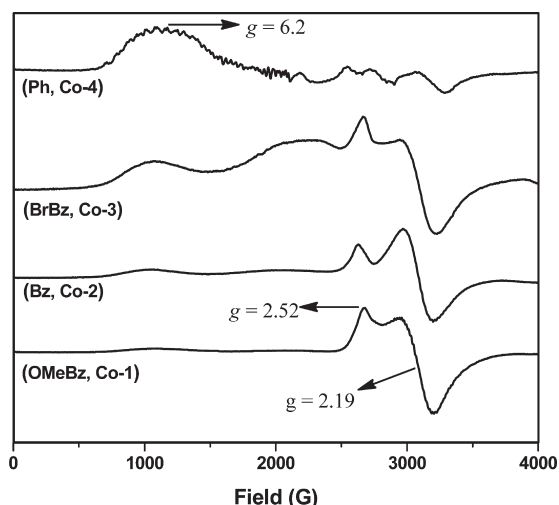


Figure 6. Plots of  $\mu_{eff}$  (BM) versus  $T$ :  $[(OMe_{Bz}NP2)Co(I)_2]$ , Co-1, (◇);  $[(Br_{Bz}NP2)Co(I)_2]$ , Co-3, (○);  $[(PhNP2)Co(I)_2]$ , Co-4, (□). Inset:  $[(BzNP2)Co(I)_2]$ , Co-2, (Δ).

range 4 to 300 K using SQUID magnetometry (Figure 6). Complexes Co-3 and Co-4 exhibit little variation in  $\mu_{eff}$  in the range 25 to 300 K. At low temperature (4 K), the magnetic moments are  $4.03 \mu_B$  and  $4.07 \mu_B$ , respectively, in reasonable agreement with the spin-only value ( $3.87 \mu_B$ ) for an  $S = 3/2$  system. Such an  $S = 3/2$  ground state is typically observed for tetrahedral  $Co^{II}$  complexes.<sup>26–29</sup>

The magnetic data for Co-2 are more difficult to interpret:  $\mu_{eff}$  decreases slowly from 300 (4.61) to 110 K ( $4.24 \mu_B$ ), then increases from 110 to 20 K. Nonetheless, the 4 K magnetic moment for Co-2 of  $4.04 \mu_B$  is nearly identical with those for Co-3 and Co-4. The data for Co-2 were obtained using crystals from the 1:1 ratio ( $BzNP2:Co$ ) reaction (the  $P2_1/c$  tetrahedral-only structure). It is possible that deviation from ideal Curie–Weiss behavior is due to trace quantities of  $Cc$  crystals (obtained from the 2:1 ratio reaction of  $BzNP2:Co$ ) that contain structural conformers Co-2/Co-2' (vide supra). We conclude that the  $RNP2-Co^{II}$  complexes are high-spin ( $S = 3/2$ ) in the solid state, as expected for tetrahedral and pseudotetrahedral structures.<sup>30</sup>

**EPR.** We recorded EPR spectra for Co-1 and Co-3 in the solid state at 4 K (Supporting Information, Figure S1). In each case, the spectrum is dominated by high-spin  $Co^{II}$  signals near  $g \approx 6$  in accord with the SQUID data. Peters and co-workers also reported consistent SQUID and solid state EPR results for both



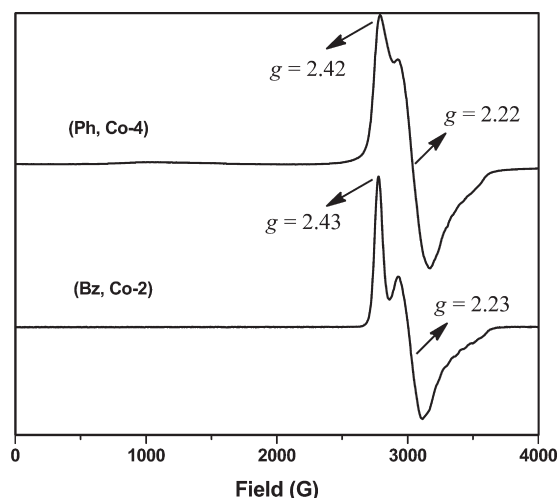
**Figure 7.** EPR spectra for  $\text{Co}^{\text{II}}$  complexes in frozen THF at 20 K (from top to bottom):  $[(\text{PhNP2})\text{Co}(\text{I})_2]$  (**Co-4**);  $[(\text{BrBzNP2})\text{Co}(\text{I})_2]$  (**Co-3**);  $[(\text{BzNP2})\text{Co}(\text{I})_2]$  (**Co-2**);  $[(\text{MeOBzNP2})\text{Co}(\text{I})_2]$  (**Co-1**). Microwave frequency, 9.453 GHz; field modulation, 20 G; microwave power, 2 mW; frequency modulation, 100 kHz.

$\{[\text{PhBP}_3]\text{Co}(\mu\text{-Br})\}_2$  and  $\{[\text{PhBP}_3]\text{Co}(\mu\text{-Br})\}_2$ .<sup>24</sup> The 20 K EPR spectra of the four  $\text{Co}^{\text{II}}$  complexes in THF are shown in Figure 7: **Co-4** exhibits a primary feature at  $g = 6.2$  (Figure 7, top spectrum) typical for distorted tetrahedral  $S = 3/2$  systems.

There is a systematic increase in the intensities of  $g \approx 2$  features with increasing N-donor strength ( $\text{Ph-N} < \text{BrBz-N} < \text{Bz-N} < \text{OMeBz-N}$  in **Co-4** < **Co-3** < **Co-2** < **Co-1**), and a concomitant decrease in the broad high-spin system near  $g \approx 6$ . As a result, the EPR spectrum of  $[(\text{OMeBzNP2})\text{Co}(\text{I})_2]$  (**Co-1**) at the opposite end of the donor strength trend is dominated by a rhombic, low-spin signal with primary features at  $g = 2.52$  and  $2.19$ . Such a spectrum is consistent with low-spin ( $S = 1/2$ )  $\text{Co}^{\text{II}}$  with vastly different axial ligands (e.g., anionic vs neutral; or neutral vs unoccupied site). The lineshapes of the low-spin signals in **Co-1**, **Co-2**, and **Co-3** closely follow those of a related square pyramidal  $\text{Co}^{\text{II}}$  phosphine complex  $[(\text{PP3})\text{Co}(\text{MeCN})]^{2+}$  ( $g = 2.11$ ).<sup>31</sup> Similar features were observed for low-spin complexes  $[\text{Co}(\text{P}^{\text{Ph}}_2\text{N}^{\text{Ph}})_2(\text{CH}_3\text{CN})](\text{BF}_4)_2$  ( $g = 2.11$ ) and  $[\text{Co}(\text{dppe})_2(\text{CH}_3\text{CN})](\text{BF}_4)_2$  ( $g = 2.20$ ) that also are square pyramidal.<sup>15,30,31</sup> Thus, it is likely that  $[(\text{OMeBzNP2})\text{Co}(\text{I})_2]$  (**Co-1**) has adopted a square pyramidal coordination geometry in THF.

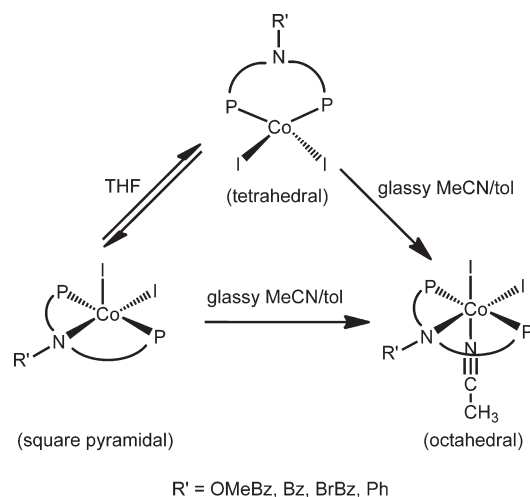
We suggest that the two conformers exist in solution whose relative populations are influenced by the ligand substituent. Correspondingly, the EPR spectra in Figure 7 clearly show that as the N-substituent becomes more strongly donating, the EPR signal attributable to the square pyramidal conformer is dominant. The  $-\text{OMe}$  appended ligand strongly enforces the five-coordinate geometry of  $[(\text{OMeBzNP2})\text{Co}(\text{I})_2]$  (**Co-1**). In contrast, the  $[(\text{PhNP2})\text{Co}(\text{I})_2]$  (**Co-4**) EPR spectrum is consistent *only* with a tetrahedral geometry, while those of **Co-3** and **Co-2** can be interpreted in terms of mixtures of conformers. It is apparent that subtle differences in ligand substituent can tune the coordination modes of NP2-type ligands.

**Frozen MeCN/tol Glass.** We observed further dynamic behavior of the NP2 ligands in EPR experiments performed in MeCN. The complex derived from the weakest N-donor,  $[(\text{PhNP2})\text{Co}(\text{I})_2]$  (**Co-4**), displays an EPR spectrum (Figure 8, top



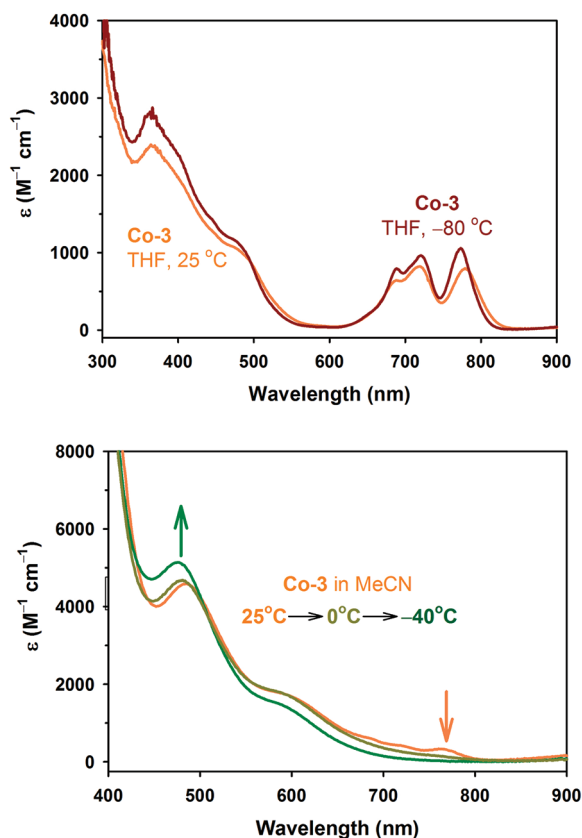
**Figure 8.** EPR spectra of  $[(\text{BzNP2})\text{Co}(\text{I})_2]$  (**Co-2**) and  $[(\text{PhNP2})\text{Co}(\text{I})_2]$  (**Co-4**) in frozen MeCN/tol glass at 20 K.

### Scheme 5. Coordination Modes of NP2 $\text{Co}^{\text{II}}$ Complexes in Solutions



spectrum) in MeCN/tol (3:1, 20 K) that is dominated by low-spin features ( $g = 2.42, 2.22$ ) that are consistent with a five-coordinate geometry. The complex  $[(\text{BzNP2})\text{Co}(\text{I})_2]$  (**Co-2**) in frozen MeCN/tol also exhibits exclusively low-spin features ( $g = 2.43, 2.22$ ; Figure 8, bottom spectrum). In both cases, it is likely that conversion to the square pyramidal (or octahedral) conformer is facilitated by coordination of MeCN. For comparison,  $[(\text{PP3})\text{Co}(\text{MeCN})]^{2+}$ ,  $[\text{Co}(\text{P}^{\text{Ph}}_2\text{N}^{\text{Ph}})_2(\text{CH}_3\text{CN})]^{2+}$ , and  $[\text{Co}(\text{dppe})_2(\text{CH}_3\text{CN})]^{2+}$  each exhibit coordinated MeCN in a square pyramidal geometry. It is well-known that  $\text{M}^{\text{II}}$  centers in octahedral or square pyramidal geometries have a strong preference for back-bonding ligands such as MeCN,  $\text{CN}^-$ , and py because of strong  $\{d_\pi(\text{M})|\pi^*(\text{L})\}$  overlap. This is in contrast to the relatively low affinity for *tetrahedral*  $\text{M}^{\text{II}}$  centers for back-bonding ligands.

In our case, coordination of the N-donor of the NP2 backbone is likely driven by the high stability of the two 5-membered  $\text{P-N-P}$  chelate rings that form the equatorial plane. Once a square pyramidal unit is established, MeCN could facilitate the formation of octahedral geometry bearing the NP2 and  $\text{I}^-$  donors in the



**Figure 9.** (Top) UV/vis spectra of Co-3 measured in THF at 25 and  $-80^{\circ}\text{C}$ . (Bottom) UV/vis spectra of Co-3 in MeCN at 25, 0, and  $-40^{\circ}\text{C}$ .

equatorial plane, while MeCN and the second  $\text{I}^{-}$  occupy axial positions (see Scheme 5). An octahedral formulation is consistent with the finding that all NP2 cobalt complexes exhibit low-spin EPR signals in MeCN. Overall, the EPR experiments illustrate the role of solvent (MeCN versus THF) in modulating the dual coordination modes of NP2 ligands.

**UV/vis Absorption Spectra.** We also investigated the spin states of the cobalt complexes by UV/vis spectrophotometry in THF and MeCN. In THF solution at  $25^{\circ}\text{C}$ , all of the complexes exhibit the following: Co-3 exhibits peaks at 780 and 720 nm ( $790$  and  $910\text{ M}^{-1}\text{ cm}^{-1}$ , respectively), which we assign high-spin  $\text{Co}^{\text{II}}$  LF transitions (Figure 9, top). The same solution at  $-80^{\circ}\text{C}$  exhibits slightly sharper features at 785 and 725 nm of comparable intensity, suggesting that even at this low temperature Co-3 remains high-spin in THF. In contrast, the spectrum of Co-3 in MeCN ( $25^{\circ}\text{C}$ ) exhibits a peak near 800 nm that is much less intense ( $\sim 250\text{ M}^{-1}\text{ cm}^{-1}$ ). Furthermore, as the MeCN solution of Co-3 is cooled first to  $0^{\circ}\text{C}$  and then  $-40^{\circ}\text{C}$ , the feature near 800 nm disappears (Figure 9, bottom), consistent with the finding that only a low-spin  $\text{Co}^{\text{II}}$  signal is observed in EPR experiments in MeCN at low temperatures (20 to 80 K). We conclude that there is a high/low-spin equilibrium (as evident in the EPR spectra) in MeCN solution, and that the low-spin state is strongly favored at lower temperatures (below  $0^{\circ}\text{C}$ ). In contrast, THF solutions of Co-3 must be cooled to much lower temperatures (less than  $-80^{\circ}\text{C}$ ) to observe even partial populations of the low-spin conformer (EPR experiments). We found similar behavior for Co-1, Co-2, and Co-4 with slightly

different high-spin/low-spin ratios that correlate with the donor strength of the ligand.

In summary, we have synthesized a series of NP2 type of ligands and corresponding  $\text{Co}^{\text{II}}$  and  $\text{Ni}^{\text{II}}$  complexes. From the crystal structures of these metal complexes, we have found that NP2 ligands exhibit dual coordination modes. The dual coordination modes are due to the geometric preference of the metal center:  $\text{Co}^{\text{II}}$  (tetrahedral) and  $\text{Ni}^{\text{II}}$  (square planar), best exhibited by the unusual crystal Cc structure containing Co-2/Co-2' with two conformers in a single unit cell. We intend to exploit this facile N-donor ligation/deligation property in designs of  $\text{M}^{\text{II}}$  complexes for reactions involving activation of organic substrates.

## ■ ASSOCIATED CONTENT

**S Supporting Information.** Crystal structure data for all complexes (CIF files), and solid state EPR spectra of Co-1 and Co-3 (Figure S1). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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