Mononuclear Nickel(II) Complexes with Schiff Base Ligands: Synthesis, Characterization, and Catalytic Activity in Norbornene Polymerization

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Abstract: The nickel(II) catalyst has manifested higher catalytic activity compared to that of other late transition metal catalysts for norbornene polymerization. Therefore, several structurally similar trans-nickel(II) compounds of N,O-chelate bidentate ligands were synthesized and characterized. Both the electronic effect and the steric hindrance influence polymerization. The molecular structures of 2, 4 and 5 were further confirmed by single-crystal X-ray diffraction.

Keywords: Schiff base; X-ray crystals; catalysis; polymerization; nickel(II) complex

1. Introduction

Over the past two decades, polynorbornene (PNB) has been widely utilized in industrial production because of its excellent physical and chemical properties, including its high solubility in ordinary organic solvents, its excellent heat resistivity, and its optical transparency [1–4]. There are three pathways for norbornene polymerization (Scheme 1): (i) Ring-opening metathesis polymerization (ROMP). The obtained product still contains double bonds in the backbone of polynorbornene [5]. (ii) Cationic or radical polymerization. Polynorbornenes synthesized by this route often show low molecular weights [6]. (iii) Vinyl-type polymerization. The bicyclic motifs remain in the polymer chain of the polynorbornene given via this polymerization route [7]. It was obtained first by using a TiCl4-based Ziegler catalyst, but these and subsequent zirconocene/MAO catalytic systems perform with lower activities [8–10]. The products (PNB) displays a characteristically rigid random coil conformation, which shows a restricted rotation around the main chain and exhibits high thermal stability (Tg > 350 °C).

Scheme 1. Three different types of polymerization for norbornene.
Under the stimulation of academic and commercial factors, different transition metal complexes based on various ligands, such as bidentate ligands N=N [11,12], N=O [13–17], N=P [18], and P=P [19] and tridentate ligands N=N=N [20], N=N=O [21], and N=P=N [22], were designed and prepared for olefin polymerization. Among these metal complexes, Ni-based catalysts are best known to oligomerize ethylene and dimerize propylene and higher R-olefins because, before 1995, nickel(II) metal was generally thought to prefer α-hydride elimination followed by reductive elimination [23–26]. However, transition-metal complexes with ligands containing dissimilar donor atoms have been widely studied, primarily for their applications in important homogeneous catalytic processes [27–29]. In particular, the complexes bearing bidentate N=O ligands have drawn more attention than ever before. Additionally, on the basis of previous reports, nickel(II) complexes with N=O ligands often exhibited good catalytic activity for olefin polymerization [13–15].

We are always interested in studying novel intramolecularly coordinated nickel(II) complexes with polymerization activity. Here, a series of mononuclear nickel(II) complexes based on the bis-N=O-chelate ligand was designed and synthesized so that their polymerization activity could be investigated. These complexes exhibited catalytic activity that is good for the polymerization of norbornene in the presence of methylaluminoxane (MAO) as a co-catalyst. Moreover, the effects that influenced catalytic behavior are herein discussed.

2. Results and Discussion

2.1. Synthesis of N,O Bidentate Ligands HL1–HL5

According to previous methods [30–32], the bidentate ligands HL1–HL5 were obtained in high yields by the reaction between 2-hydroxy-1-naphthaldehyde and corresponding aryl amines in ethanol solutions. They were isolated as yellow solids in high yields (Scheme 2). The 1H-NMR spectra and elemental analysis data all ascertain the identity of the ligands.

Scheme 2. Synthesis of N,O-chelate bidentate ligands HL1–HL5.

2.2. Synthesis of N,O-Coordinate Ni(II) Complexes 1–5

Analogous to the procedure of preparing copper(II) complexes [13–15], the reactions of Schiff base ligands HL1–HL5 with nickel(II) acetate yielded the N,O-chelate Ni(II) Complexes 1–5 in good yields (Scheme 3). The products precipitated from the solution after the reaction was cooled to room temperature. Complexes 1–5 are soluble in toluene and dichloromethane but slightly soluble in diethyl ether and petroleum ether. They are stable at room temperature in air. No decomposition was observed even after refluxing in toluene for several hours. HRMS spectra of complexes 1–5 have exhibited strong molecular peaks (Figures S1–S5). Meanwhile, TGA characterization confirmed their thermal stability (Figure S6). However, the 1H and 13C-NMR spectra of these complexes are not informative because of the para-magnetism of the nickel(II) complexes. The IR spectra of N,O-chelate Ni(II) complexes are similar to each other. The common feature of these complexes is that the C=N stretching vibration of the ligands (1625–1635 cm−1) are shifted to lower frequencies (1610 cm−1).
2.3. UV–Vis Spectroscopy

Figure 1 shows the UV–Vis spectra of the nickel(II) Complexes 1–5 in dichloromethane solutions. The UV–Vis absorption spectral data is presented in Table 1. The absorption spectra of all complexes is characterized by intense absorption bands in the range of 319–324 nm, which are assigned to the \( \pi \rightarrow \pi^* \) molecular orbitals localized on the imine group and the aromatic ring [33]. The lower-intensity absorption bands in the 366–382 nm region are assigned to the metal-to-ligand charge transfer (MLCT) [34]. The ultraviolet spectra measurements of these complexes demonstrate that their electronic structures are similar to each other.

![UV–Vis Spectra of Complexes 1–5](image)

**Figure 1.** UV–Vis spectra of Complexes 1–5 (3.59 × 10\(^{-6}\) mol·dm\(^{-3}\) in CH\(_2\)Cl\(_2\)).

| Complex | \( \lambda_{abs}/nm \) (\( \varepsilon/\text{dm}^3\cdot\text{mol}^{-1}\cdot\text{cm}^{-1} \)) |
|---------|---------------------------------|
| 1       | 319 (2.97 × 10\(^4\)); 378 (2.67 × 10\(^4\)) |
| 2       | 324 (2.28 × 10\(^4\)); 382 (3.06 × 10\(^4\)) |
| 3       | 320 (2.45 × 10\(^4\)); 382 (2.24 × 10\(^4\)) |
| 4       | 319 (2.17 × 10\(^4\)); 377 (2.26 × 10\(^4\)) |
| 5       | 316 (3.40 × 10\(^4\)); 366 (2.14 × 10\(^4\)) |

2.4. X-ray Crystallographic

In order to identify the structures of these nickel(II) complexes, single-crystal X-ray diffraction measurement was carried out on Complexes 2, 4, and 5. Suitable crystals were obtained by slow diffusion of n-hexane into their concentrated solution of dichloromethane. Selected bond lengths and

![X-ray Crystallographic Image](image)
angles (Table S1) and their crystal data (Table S2) are listed in the supporting information. As shown in Figure 2, they have analogous structures in a solid state. Their structures are centrosymmetric with the symmetry centers located on the metal centers. Although previous reports indicated that the steric and electron effects of the substituent groups on the aromatic rings of bulky four-coordinated transition metal complexes probably distort the geometry of the metal center from the planar coordination to the pseudo-tetrahedral geometry [35–37]; however, the NiN$_2$O$_2$ chromophores of the three nickel(II) complexes are absolutely planar with the dihedral angles of 0 between the planes of N(1)–Ni(1)–O(1) and N(1A)–Ni(1)–O(1A). The Ni(1)–N(1) and Ni(1)–O(1) distances are both located in the range of known values for these bonds in analogous complexes [38]. The structures of the three complexes are similar to each other except for the slight differences in bond distance and angles. We failed to obtain single crystals of other nickel(II) complexes after many attempts.

Figure 2. Molecular structures of 2, 4, and 5 with 30% probability ellipsoids. Hydrogen atoms are omitted for clarity.

2.5. Polymerization of Norbornene

The catalytic behavior of these nickel(II) complexes was investigated based on our previous work [39]. Preliminary experiments on norbornene polymerization were carried out in the presence of MAO as a co-catalyst. We chose chlorobenzene as the reaction solvent for the polymerization process because the polar solvent was able to improve the catalytic performances in norbornene vinyl polymerization (Scheme 4). Experimental results are summarized in Table 2. No catalytic activity
The obtained polynorbornenes were characterized by IR and-NMR spectroscopy (Figure S7). The characteristic peaks of these polymers at approximately 942 cm⁻¹ were analogous. These absorption
peaks at about 942 cm$^{-1}$ were identified to the ring system of bicycle heptane [40]. There are no absorptions at about 735 and 960 cm$^{-1}$, suggesting that no ROMP structure of polynorbornenes were found, because the two absorptions are assign to the trans and cis forms of double bonds, respectively, which are characteristic of the ROMP structure of polynorbornenes [41–43]. The $^1$H HMR polynorbornenes displayed four groups of signals in the range of $\delta$ 1.0–3.0 ppm. The absence of the resonances at approximately $\delta$ 5.1 and 5.3 ppm in the $^1$H-NMR spectra further confirms that the polymers are vinyl-type addition products [44].

3. Experimental Section

3.1. General Data

All experiments were carried out under an atmosphere of nitrogen using standard Schlenk techniques. Ethanol and methanol were used as commercial products without further purification. $^1$H-NMR (500 MHz) spectra was measured with a Bruker DMX-500 spectrometer (Bruker, Washington, DC, USA). Elemental analysis was performed on an Elementar vario EL III analyzer (Elementar, Langenselbold, Germany). UV–Vis absorption spectra were recorded using a UV 765 spectrophotometer (Shimadzu, Kyoto, Japan) with quartz cuvettes with a 1 cm path length. IR (KBr) spectra were measured with the Nicolet FT-IR spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA).

3.2. Synthesis of Ligands HL1–HL5

The Schiff base ligands HL1–HL5 were synthesized by a routine method. 2-Hydroxy-1-naphthaldehyde (5.0 mmol) and corresponding amines (5.0 mmol) were combined and heated to reflux in ethanol for 6 h in the presence of catalytic amount of ethyl acetate, resulting in a color change from colorless to bright yellow. Solvent was concentrated under reduced pressure and stored at −10 °C overnight, and further purification was achieved by filtration and washed with CH$_3$OH (3 × 10 mL). The collected solid was dried under vacuum.

HL1: yellow solid; 1.13 g, 92% yield. $^1$H-NMR (500 MHz, CDCl$_3$, 25 °C): $\delta$ 15.54 (s, 1H), 9.36 (d, $J = 4.5$ Hz, 1H), 8.13 (d, $J = 8.5$ Hz, 1H), 7.83 (d, $J = 9.5$ Hz, 1H), 7.74 (d, $J = 8.0$ Hz, 1H), 7.56 (t, $J = 9.0$ Hz, 1H), 7.51 (t, $J = 9.0$ Hz, 2H), 7.41–7.30 (m, 5H). IR (KBr, disk): $\nu$ 3066, 1621, 1568, 1488, 1331, 821, 750, 695 cm$^{-1}$. Elemental analysis calcd (%) for C$_{18}$H$_{13}$NO: C 82.57, H 5.30, N 5.66, found: C 82.68, H 5.35, N 5.47.

HL2: yellow solid; 1.22 g, 88% yield. $^1$H-NMR (500 MHz, CDCl$_3$, 25 °C): $\delta$ 15.71 (s, 1H), 9.35 (d, $J = 4.0$ Hz, 1H), 8.14 (d, $J = 8.5$ Hz, 1H), 7.82 (d, $J = 9.0$ Hz, 1H), 7.75 (d, $J = 8.0$ Hz, 1H), 7.56 (t, $J = 9.6$ Hz, 1H), 7.38–7.34 (m, 3H), 7.14 (d, $J = 9.0$ Hz, 1H), 7.02 (d, $J = 9.0$ Hz, 2H), 3.88 (s, 3H). IR (KBr, disk): $\nu$ 3051, 1621, 1507, 1302, 821, 750, 502 cm$^{-1}$. Elemental analysis calcd (%) for C$_{18}$H$_{13}$NO$_2$: C 77.96, H 5.45, N 5.05, found: C 77.79, H 5.38, N 5.23.

HL3: yellow solid; 1.41 g, 85% yield. $^1$H-NMR (500 MHz, CDCl$_3$, 25 °C): $\delta$ 15.23 (s, 1H), 9.08 (d, $J = 3.0$ Hz, 1H), 8.00 (d, $J = 8.5$ Hz, 1H), 7.88 (d, $J = 9.0$ Hz, 1H), 7.78 (d, $J = 8.0$ Hz, 1H), 7.52 (t, $J = 8.0$ Hz, 1H), 7.37 (t, $J = 7.5$ Hz, 1H), 7.26–7.25 (m, 3H), 7.21 (d, $J = 9.5$ Hz, 1H), 3.16–3.07 (m, 2H), 1.24 (d, $J = 7.0$ Hz, 12H). IR (KBr, disk): $\nu$ 3062, 1624, 1584, 1320, 3051, 2928, 1627, 1584, 1320, 1156, 753, 595 cm$^{-1}$. Elemental analysis calcd (%) for C$_{23}$H$_{25}$NO: C 83.34, H 7.60, N 4.23, found: C 83.39, H 7.53, N 4.36.

HL4: yellow solid; 1.38 g, 88% yield. $^1$H-NMR (500 MHz, CDCl$_3$, 25 °C): $\delta$ 15.12 (s, 1H), 9.40 (d, $J = 2.5$ Hz, 1H), 8.15 (d, $J = 8.5$ Hz, 1H), 7.88 (d, $J = 9.5$ Hz, 1H), 7.76–7.73 (m, 3H), 7.59 (t, $J = 7.5$ Hz, 1H), 7.46 (d, $J = 8.5$ Hz, 2H), 7.41 (t, $J = 7.5$ Hz, 1H), 7.15 (d, $J = 9.0$ Hz, 1H). IR (KBr, disk): $\nu$ 3057, 1627, 1584, 1320, 1156, 753, 595 cm$^{-1}$. Elemental analysis calcd (%) for C$_{18}$H$_{12}$F$_3$NO: C 68.57, H 3.84, N 4.44, found: C 68.63, H 3.85, N 4.55.

HL5: yellow solid; 1.14 g, 84% yield. $^1$H-NMR (500 MHz, CDCl$_3$, 25 °C): $\delta$ 14.94 (s, 1H), 9.40 (d, $J = 3.0$ Hz, 1H), 8.15 (d, $J = 8.5$ Hz, 1H), 7.90 (d, $J = 9.5$ Hz, 1H), 7.79 (d, $J = 8.5$ Hz, 3H), 7.60 (t, $J = 7.5$ Hz, 1H).
The PNB was isolated by filtration, washed with ethanol, and dried at 80 ◦C. All calculations were performed using the Bruker program Smart. Polymerization bottle (50 mL) under a nitrogen atmosphere. After stirring at 30 ◦C for 5 h, the deep green solid was collected by filtration and washed with methanol for several times.

3.3. Synthesis of Nickel(II) Complexes 1–5

A mixture of acetic acid nickel(II) salt Ni(OAc)2·H2O (0.15 mmol) and methanol (10 mL) was added to the solution of the ligands L1–L5 (0.3 mmol) in methanol (10 mL) [15]. After stirring at 60 ◦C for 5 h, the deep green solid was collected by filtration and washed with methanol for several times.

1: deep green solid; 595 mg, 72% yield. IR (KBr, disk): υ 1612, 1574, 1530, 751.71, 697 cm−1. Elemental analysis calcd (%) for C34H24N2NiO2: C 74.08, H 4.39, N 5.08; Found: C 74.00, H 4.37, N 5.11. ESI-HRMS: m/z calcd for C34H24N2NiO2 [M + H]+: 551.1270; Found: 551.1261.

2: deep green solid; 713 mg, 78% yield. IR (KBr, disk): υ 1615, 1598, 1536, 1500, 1238, 1185, 822, 748 cm−1. Elemental analysis calcd (%) for C36H26N2NiO4: C 70.73, H 4.62, N 4.58; Found: C 70.79, H 4.52, N 4.57. ESI-HRMS: m/z calcd for C36H26N2NiO4 [M + H]+: 611.1481; Found: 611.1495.

3: brown solid; 612 mg, 68% yield. IR (KBr, disk): υ 1598, 1530, 1497, 1433, 1364, 1190, 827, 746 cm−1. Elemental analysis calcd (%) for C36H22N4NiO2: C 71.91, H 3.69, N 9.32; Found: C 71.96, H 3.67, N 9.31. ESI-HRMS: m/z calcd for C36H22N4NiO2 [M + H]+: 601.1174; Found: 601.1172.

4: brown solid; 761 mg, 74% yield. IR (KBr, disk): υ 1616, 1602, 1580, 1536, 1454, 1326, 1123, 832, 747 cm−1. Elemental analysis calcd (%) for C36H22F6NiO2: C 62.92, H 3.23, N 4.08; Found: C 62.96, H 3.27, N 4.02. ESI-HRMS: m/z calcd for C36H22F6NiO2 [M + H]+: 687.1017; Found: 687.1030.

5: brown solid; 776 mg, 72% yield. IR (KBr, disk): υ 1615, 1603, 1580, 1537, 1364, 827, 741 cm−1. Elemental analysis calcd (%) for C46H48N2O2: C 76.78, H 6.72, N 3.89; Found: C 76.78, H 6.77, N 3.86. ESI-HRMS: m/z calcd for C46H48N2O2 [M + H]+: 719.3148; Found: 719.3135.

3.4. Norbornene Polymerization

In a typical procedure, 1 µmol of nickel(II) Complex 1 in 1.0 mL of chlorobenzene, 1.80 g of norbornene in 3 mL of chlorobenzene and 6 mL of fresh chlorobenzene were added to a special polymerization bottle (50 mL) under a nitrogen atmosphere. After stirring at 30 ◦C for 10 min, a certain amount of MAO was charged into the polymerization system via a syringe and the reaction was started. After 30 min, acidic ethanol (Vethanol:Vconc.HCl = 20:1) was added to terminate the reaction. The PNB was isolated by filtration, washed with ethanol, and dried at 80 ◦C for 24 h under vacuum. For all polymerization procedures, the total reaction volume was 10.0 mL, which could be achieved by varying the amount of chlorobenzene when necessary. The viscosity average molar masses (Mn) of the PNB were obtained in chlorobenzene at 25 ◦C using Mark–Houwink coefficients.

3.5. X-ray Crystallography

Data of 2, 4, and 5 were collected on a Bruker Smart APEX CCD diffractometer with graphite-monochromated MoKα radiation (λ = 0.71073 Å). All data were collected at room temperature, and the structures were solved by direct methods and subsequently refined on F2 by using full-matrix least-squares techniques (SHELXL) [45]. SADABS [46] absorption corrections were applied to the data, all non-hydrogen atoms were refined anisotropically, and hydrogen atoms were located at calculated positions. All calculations were performed using the Bruker program Smart.

4. Conclusions

In this report, a series of N,O-chelate Schiff base Ni(II) complexes containing 2-hydroxy-1-naphthaldehyde ligands was synthesized and characterized by IR spectra, UV, 1H-NMR, and single-crystal X-ray diffraction analysis. Structural analysis of 2, 4, and 5 confirms that the nickel(II)
atom coordinates with two ligands. The results of this experiment demonstrate that these nickel(II) complexes have extremely high catalytic activity ($3.06 \times 10^6$ gPNB mol$^{-1}$ Ni h$^{-1}$) for norbornene polymerization when using MAO as a co-catalyst. The utilization of these nickel(II) complexes as catalysts in the oxidation of olefins is currently underway in our laboratory.

**Supplementary Materials:** The following are available online at www.mdpi.com/2073-4360/9/3/105/s1, Figure S1: HRMS of complex 1. Figure S2: HRMS of complex 2. Figure S3: HRMS of complex 3. Figure S4: HRMS of complex 4. Figure S5: HRMS of complex 5. Figure S6: TGA curves of complexes 1–5. Figure S7: IR spectrum and $^1$H NMR spectrum of PNB. Table S1: Selected Bond Lengths (Å) and Angles (°) for Complexes 2, 4, and 5. Table S2: Crystal data for Complexes 2, 4, and 5.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**Abbreviations**

PNB polynorbornenes
MAO methylaluminoxane

**References**

1. Janiak, C.; Lassahn, P.G. Metal catalysts for the vinyl Polymerization of norbornene. *J. Mol. Catal. A Chem.* **2001**, *166*, 193–209. [CrossRef]
2. Janiak, C.; Lassahn, P.G. The Vinyl Homopolymerization of Norbornene. *Macromol. Rapid Commun.* **2001**, *22*, 479–493. [CrossRef]
3. Grove, N.R.; Kohl, P.A.; Allen, S.A.B.; Jayaraman, S.; Shick, R. Functionalized polynorbornene dielectric polymers: Adhesion and mechanical properties. *J. Polym. Sci. B Polym. Phys.* **1999**, *37*, 3003–3010. [CrossRef]
4. Lee, D.; Choi, M.C.; Ha, C.S. Polynorbornene dicarboximide/amine functionalized graphene hybrids for potential oxygen barrier films. *J. Polym. Sci. Part A Polym. Chem.* **2012**, *50*, 1611–1621. [CrossRef]
5. Ivin, K.J.; Mol, J.C. *Olefin Metathesis and Metathesis Polymerization*; Academic Press: San Diego, CA, USA, 1997.
6. Chen, Z.; Trudell, M.L. Chemistry of 7-Azabicyclo[2.2.1]hepta-2,5-dienes, 7-Azabicyclo [2.2.1]hept-2-enes, and 7-Azabicyclo [2.2.1]heptanes. *Chem. Rev.* **1996**, *96*, 1179–1194. [CrossRef] [PubMed]
7. Mast, C.; Krieger, M.; Dehnicek, K.; Greiner, A. Vinyl-type polymerization of norbornene by a nickel-based catalyst with phosphoraneiminato ligands. *Macromol. Rapid Commun.* **1999**, *20*, 232–235. [CrossRef]
8. Tlenkopatchev, M.; Fomine, S.; Miranda, E.; Fomina, L.; Ogawa, T. Synthesis of Polynorbornene Containing Fluorescein Moiety. *Polym. J.* **1995**, *27*, 1173–1179. [CrossRef]
9. Kaminsky, W.; Bark, A.; Arndt, M. New polymers by homogenous zirconocene/aluminoxane catalysts. *Makromol. Chem. Macromol. Symp.* **1991**, *47*, 83–93. [CrossRef]
10. Kaminsky, W.; Noll, A. Copolymerization of norbornene and ethene with homogenous zirconocenes/methylaluminoxane catalysts. *Polym. Bull.* **1993**, *31*, 175–182. [CrossRef]
11. Johnson, L.K.; Brookhart, S.M. Copolymerization of Ethylene and Propylene with Functionalized Vinyl Monomers by Palladium(II) Catalysts. *J. Am. Chem. Soc.* **1996**, *118*, 267–268. [CrossRef]
12. Avent, A.G.; Hitchcock, P.B.; Lappert, M.F.; Sablong, R.; Severn, J.R. Synthesis, Structures, Characterization, Dynamic Behavior, and Reactions of Novel Late Transition Metal(II) 1-Azaallyls. *Organometallics* **2004**, *23*, 2591–2600. [CrossRef]
13. Yao, Z.-J.; Li, K.; Zhang, J.-Y.; Wang, Y.; Deng, W. Synthesis, Characterization and Polymerization Activity of Copper Complexes with N, O-Chelate Ligands. *Inorg. Chem. Acta* **2016**, *450*, 118–123. [CrossRef]
14. Wang, X.; Jin, G.-X. Preparation, Structure, and Olefin Polymerization Behavior of a Picolyl-Functionalized Carborane Nickel(II) Complex. *Organometallics* **2004**, *23*, 6319–6322. [CrossRef]
15. Meng, X.; Tang, G.-R.; Jin, G.-X. Vinyl and ring-opening metathesis polymerization of norbornene with novel half-sandwich iridium(III) complexes bearing hydroxyindamine ligands. Chem. Commun. 2008, 3178–3180. [CrossRef] [PubMed]
16. Huang, R.; He, X.; Chen, Y.; Nie, H.; Zhou, W. Homo- and copolymerization of norbornene and 5-norbornene-2-yl acetate with bis-(β-ketonaphthylamino)palladium(II)/B(C₆H₅)₃ catalytic system. Polym. Adv. Technol. 2012, 23, 483–490. [CrossRef]
17. Carlini, C.; Martinelli, M.; Galletti, A.M.R.; Sbrana, G. Vinyl polymerization of norbornene by bis(nitro-substitutedsalicylaldiminate)nickel(II)/methylaluminoxane catalysts. J. Polym. Sci. Part A Polym. Chem. 2006, 44, 1514–1521. [CrossRef]
18. Wang, H.-Y.; Jin, G.-X. Highly Active Neutral Nickel(II) Complexes Bearing PN-Chelate Ligands: Synthesis, Characterization and Their Application to Addition Polymerization of Norbornene. Eur. J. Inorg. Chem. 2005, 9, 1665–1670. [CrossRef]
19. Vougioukalakis, G.C.; Stamatopoulos, I.; Petzetakis, N.; Raptopouloou, C.P.; Psycharis, V.; Terzis, A.; Kyrtisis, P.; Pitsikalis, M.; Hadjichristidis, N. Controlled vinyl-type polymerization of norbornene with a Nickel(II) diphosphinoamine/methylaluminoxane catalytic system. J. Polym. Sci. A Polym. Chem. 2009, 47, 5241–5250. [CrossRef]
20. Antonov, A.A.; Semikolenova, N.V.; Zakharov, V.A.; Zhang, W.; Wang, Y.; Sun, W.-H.; Talsi, E.P.; Bryliakov, K.P. Vinyl Polymerization of Norbornene on Nickel Complexes with Bis(imino)pyridine Ligands Containing Electron-Withdrawing Groups. Organometallics 2012, 31, 1143–1149. [CrossRef]
21. Du, J.; Li, L.-J.; Li, Y. Ni(II) complexes bearing 2-aryliminobenzimidazole: synthesis, structure and ethylene oligomerization study. Inorg. Chem. Commun. 2005, 8, 246–248. [CrossRef]
22. Shi, X.-C.; Jin, G.-X. Synthesis and Characterization of Nickel(II) and Palladium(II) Complexes based on Tridentate [N-NP] and [N-NS] Ligands and Their Applications in Norbornene Polymerization. Organometallics 2012, 31, 4748–4754. [CrossRef]
23. Johnson, L.K.; Killian, C.M.; Brookhart, M. New Pd(II)- and Ni(II)-Based Catalysts for Polymerization of Ethylene and alpha-Olefins. J. Am. Chem. Soc. 1995, 117, 6414–6415. [CrossRef]
24. Gates, D.P.; Svojda, S.A.; Onate, E.; Killian, C.M.; Johnson, L.K.; White, P.S.; Brookhart, M. Synthesis of Branched Polyethylene Using (α-Diimine)nickel(II) Catalysts: Influence of Temperature, Ethylene Pressure, and Ligand Structure on Polymer Properties. Macromolecules 2000, 33, 2320–2334. [CrossRef]
25. Guan, Z.; Cotts, P.M.; McCord, E.F.; McLain, S. Chain Walking: A New Strategy to Control Polymer Topology. J. Sci. 1999, 283, 2059–2062. [CrossRef]
26. Killian, C.M.; Tempel, D.J.; Johnson, L.K.; Brookhart, M. Living Polymerization of α-Olefins Using NiII-α-Diimine Catalysts. Synthesis of New Block Polymers Based on α-Olefins. J. Am. Chem. Soc. 1996, 118, 11664–11665. [CrossRef]
27. Takei, I.; Nishibayashi, Y.; Arikawa, Y.; Uemura, S.; Hirai, M. Iridium-Catalyzed Asymmetric Hydrosilylation of Imines Using Chiral Oxazolidinyl-Phosphine Ligands. Organometallics 1999, 18, 2271–2274. [CrossRef]
28. Yang, H.; Alvarez-Gressier, M.; Lugan, N.; Mathieu, R. Ruthenium(II) Complexes Containing Optically Active Hemilabile P,N,O-Tridentate Ligands. Synthesis and Evaluation in Catalytic Asymmetric Transfer Hydrogenation of Acetophenone by Propan-2-ol. Organometallics 1997, 16, 1401–1409. [CrossRef]
29. Yang, H.; Lugan, N.; Mathieu, R. Study of the Bonding Properties of the New Ligands C₅H₃N(2-R)(6-CH₂PPhR) toward Rhodium(I). Evidence for a Dynamic Competition for Bonding between O- and N-Donor Centers When R = o-Anisyl, R = Me. Organometallics 1997, 16, 2089–2095. [CrossRef]
30. Kajimoto, T.; Tsuji, J. Preparation of benzenetetracarboxylic acids by the cobalt-catalyzed carboxylation of Schiff bases from benzene dicarbaldehydes and subsequent oxidation. J. Org. Chem. 1983, 48, 1685–1690. [CrossRef]
31. Julija, M.-S.; Marijana, V.; Draen, V.-T. NMR Spectroscopy of 2-Hydroxy-1-naphthylidine Schiff Bases with Chloro and Hydroxy Substituted Aniline Moeity. Croat. Chem. Acta 2006, 79, 489–495. [CrossRef]
32. Fasina, T.M.; Dada, R.O. Substituent effect on electronic absorption and biological properties of Schiff bases derived from aniline. J. Chem. Pharm. Res. 2013, 5, 177–181. [CrossRef]
34. Kermagoret, A.; Braunstein, P. Mono- and Dinuclear Nickel Complexes with Phosphino-, Phosphinito-, and Phosphonitopyridine Ligands: Synthesis, Structures, and Catalytic Oligomerization of Ethylene. Organometallics 2007, 27, 88–99. [CrossRef]
35. Martin, E.M.; Bereman, R.D. Synthesis and characterization of square planar and pseudo-tetrahedral M(II)N$_2$S$_2$. Inorg. Chim. Acta 1991, 188, 221–231.
36. Deb, T.; Anderson, C.M.; Chattopadhyay, S.; Ma, H.; Young, V.G., Jr.; Jensen, M.P. Steric and electronic effects on aryllithiolate coordination in the pseudotetrahedral complexes [(Tp$_{\text{Ph,Me}}$)Ni-SAr] (Tp$_{\text{Ph,Me}}$ = hydrotris[3-phenyl-5-methyl-1-pyrazolyl]borate). Dalton Trans. 2014, 43, 17489–17499. [CrossRef] [PubMed]
37. Yuan, J.; Wang, F.; Yuan, B.; Jia, Z.; Song, F.; Li, J. Highly active ortho-phenyl substituted α-diimine Nickel(II) catalysts for “chain walking polymerization” of ethylene: Synthesis of the nanosized dendritic polyethylene. J. Mol. Catal. A Chem. 2013, 370, 132–139. [CrossRef]
38. Hu, P.; Yao, Z.-J.; Wang, J.-Q.; Jin, G.-X. Synthesis, Structure, and Olefin Polymerization Behavior of Nickel Complexes with Carborane [S,C] or [S,S] Ligands. Organometallics 2011, 30, 4935–4940. [CrossRef]
39. Yao, Z.-J.; Jin, G.-X. Transition metal complexes based on carboranyl ligands containing N, P, and S donors: Synthesis, reactivity and applications. Coord. Chem. Rev. 2013, 257, 2522–2535. [CrossRef]
40. Kennedy, J.P.; Makowski, H.S.J. Carbonium ion polymerization of norbornene and its derivatives. J. Macromol. Sci. Chem. 1967, A1, 345. [CrossRef]
41. Barnes, D.A.; Benedikt, G.M.; Goodall, B.L.; Hung, S.S.; Kalamardes, H.A.; Lenhard, S.; McIntosh, L.H.; Selvy, K.T.; Shick, R.A.; Rhodes, L.F. Addition Polymerization of Norbornene-Type Monomers Using Neutral Nickel Complexes Containing Fluorinated Aryl Ligands. Macromolecules 2003, 36, 2623–2632. [CrossRef]
42. Patil, A.O.; Zushma, S.; Stibrany, R.T.; Rucker, S.P.; Wheeler, L.M. Vinyl-type polymerization of norbornene by nickel(II) bisbenzimidazole catalysts. J. Polym. Sci. Part A: Polym. Chem. 2003, 41, 2095–2106. [CrossRef]
43. Zhao, C.; Ribeiro, M.R.; de Pinho, M.N.; Subrahmanyam, V.S.; Gil, C.L.; de Lima, A.P. Structural characteristics and gas permeation properties of polynorbornenes with retained bicyclic structure. Polymer 2001, 42, 2455–2462. [CrossRef]
44. Haselwander, T.F.A.; Heitze, W.; Masoko, M. Vinylic polymerization of norbornene by Pd(II)-catalysis in the presence of ethylene. Macromol. Rapid. Commun. 1997, 18, 689–697. [CrossRef]
45. Sheldrick, G.M. SHELXL-97, Program for the Refinement of Crystal Structures; Universitat Gtötingen: Goettingen, Germany, 1997.
46. Sheldrick, G.M. SADABS (2.01), Bruker/Siemens Area Detector Absorption Correction Program; Bruker AXS: Madison, WI, USA, 1998.