Synthesis of novel photofunctional multinuclear complexes using a coupling reaction†

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Various photofunctional metal complexes with functional groups, i.e. bromo and vinyl groups, were integrated into hetero-multinuclear complexes using the Mizoroki–Heck reaction. The obtained trinuclear complexes absorb a wide range of visible light and have a long excited state lifetime and the photocatalytic ability to obtain CO2 reduction.

Introduction

Multinuclear transition-metal complexes with photofunctional properties, many of which are constructed using the same repeated metal complexes, have become of interest in recent years because of their potential use in dye-sensitised solar cells1 and light-harvesting systems.2 Hetero-multinuclear metal complexes constructed using different functional units have recently been found to be efficient photocatalysts for the oxidation of water,3,4 evolution of hydrogen,5–7 and CO2 reduction.8–13 For example, Ru(II)–Re(I) dinuclear complexes, in which the Ru(II) unit works as a photosensitiser and the Re(I) unit works as a catalyst, are effective photocatalysts for CO2 reduction because of rapid intramolecular electron transfer from the photochemically-reduced Ru(II) unit to the Re(I) unit.10

Most of these multinuclear metal complexes have been synthesised using stepwise methods with several complexation steps.14 A mononuclear complex with a multitendate ligand having one chelating moiety already coordinated to the metal centre and another able to coordinate is synthesised first, which can then react with another metal centre to afford a dinuclear complex. Various multinuclear complexes have been synthesised by repeating these processes; however, there are some limitations with respect to the product selectivity achieved using this method. For example, a bridging ligand with a number of different diimine moieties can react with a metal complex (or complexes) to give a mixture of products with different numbers of metal complexes and/or with one or more metal complexes connected to different diimine moieties.

There are several reports of one-pot syntheses of hetero-dinuclear complexes using an asymmetric bridging ligand with two different coordination sites.15 This synthetic method requires very different rates of coordination reactions of each metal ion to each coordination site for high production selectivity of one heteronuclear complex.

Homo-coupling reactions of metal complexes have recently been applied for the synthesis of asymmetric dinuclear complexes, though the isolated yields were relatively low (5.4%–8.5%).16 It has also been reported that cross-coupling reactions (Sonogashira coupling17–19 and Suzuki–Miyaura coupling20–22) were used to synthesise multinuclear complexes. In this method, each complex possessing functional groups such as a bromo group, an ethynyl group, or a boronic-acid substituent as building blocks can be connected to give a heteronuclear complex with a relatively high degree of selectivity.

Herein we report the first use of the Mizoroki–Heck reaction23,24 in a coupling reaction with different types of emissive metal complexes (Ru(II), Ir(III) and Re(I) complexes with one or more diimine ligands) to give multinuclear complexes with various photofunctional properties.

Results and discussion

Synthesis of a Re(I) dinuclear complex using the Heck reaction

(1)
We chose two types of Re(i) complexes as building blocks (eqn (1)) to determine if the Mizoroki–Heck reaction is able to couple different photofunctional metal complexes. An acetonitrile (MeCN) solution (4 mL) of Pd(OAc)$_2$ (4.5 μmol), triphenylphosphine (PPh$_3$, 9.2 μmol) and sodium acetate (AcONa, 140 μmol) at 75 °C under an Ar atmosphere for one day. Ar was pumped into the reaction mixture during synthesis. The solvent was evaporated once the reaction reached completion. An MeCN solution (4 mL) of Pd(OAc)$_2$ (4.5 μmol) and PPh$_3$ (9.2 μmol) was then added to the residue along with a small amount of air; this addition of air was needed to achieve a good yield. The solution was heated for one day. Electrospray ionisation mass spectrometry (ESI-MS) analysis of the crude products indicated three major peaks attributed to [Re(4,4-dibromo-bpy) (CO)$_2$(PEt$_3$)$_3$]$^+$ (bpv = 2,2′-bipyridine), which should be produced via debromination of [Re(Br,Et)]$^+$ (Fig. 1). The target dinuclear Re(i) complex [Re(OEt)Re(Et)]$^+$ was chromatographically isolated using silica gel and SP Sephadex as adsorbents, giving an isolated yield of 70%. Note that the reaction was much slower under anaerobic conditions, as a small amount of O$_2$ was required to accelerate the reaction.

A single peak attributed to olefinic protons was observed in the $^1$H NMR spectrum of [Re(OEt)Re(Et)]$^{2+}$ (Fig. 2). This suggests that either the cis or the trans isomer was formed. The product [Re(OEt)Re(Et)]$^{2+}$ was assumed to be the trans isomer because the Re(i) units on either side were bulky. Such a low-field resonance of the olefinic protons (δ = 8.07) was similar to the resonance seen for trans-1,2-bis(4′-methyl-2,2′-bipyridine)ethene. The high resolution mass spectrum and $^{31}$P NMR spectrum clearly show that neither the P(OEt)$_3$ nor the PEt$_3$ ligands on the Re(i) units have been substituted with the coupling reagents.

It should be emphasised that the selective synthesis of only one type of dinuclear complex with an asymmetric bridging ligand, such as [Re(OEt)Re(Et)]$^{2+}$, is difficult using ordinary methods, which possibly results in a mixture of four types of dinuclear complexes, i.e. two types of complexes with identical phosphine ligands in both units and two structural isomers of complexes with two different phosphine ligands in each unit.

### Synthesis of various trinuclear complexes using the Heck reaction

A similar reaction could successfully be used to synthesise various trinuclear complexes. At the centre of each of these products was a Re(i) complex with a bpy ligand and two other metal complexes as substituents (eqn (2)). A Re(i) bis-carbonyl complex with two bromo groups, [Re(4,4-dibromo-bpy)- (CO)$_2$(PPh$_3$)$_3$]$^+$, reacted with various photofunctional complexes possessing a vinyl group, i.e. [Re(C=C,OEt)]$^+$, [Ru$_{14}$(bpy)$_8$(vbpy)$_2$]$^{2+}$ (vbpy = 4-methyl-4′-vinyl-bpy), [Ru$^{dmb}$(dmb)$_2$(vbpy)$_2$]$^{2+}$ ([Ru(C=C,dmb)$_2$]$^{2+}$, dmb = 4,4′-dimethyl-bpy) and [Ir$_{14}$(ppy)(vbpy)]$^+$ ([Ir(C=C,ppy)]$^+$, ppy = 2-phenyl-pyridine). This was performed under the same reaction conditions as were used to synthesise [Re(OEt)Re(Et)]$^{2+}$, with the exception of repeating both the heating and addition of the MeCN solution of Pd(OAc)$_2$ and PPh$_3$ twice, in the case of [Ru(bpy)$_4$Re(Ph)]$^{2+}$ and [Ir(ppy)$_3$Re(Ph)]$^{2+}$. The trinuclear complexes could be separated using size exclusion chromatography (SEC) or ion-exchange chromatography. The trinuclear complexes with Ru$_n$ or Re$_i$ in both edge units, i.e. [Re(OEt)$_2$Re(Ph)]$^{2+}$, [Ru(bpy)$_4$Re(Ph)]$^{2+}$ and [Ru(dmb)$_2$Re(Ph)]$^{2+}$, were obtained in 31%, 41% and 32% yields, respectively.

ESI-MS analysis of the solution after the reaction between [Re(4,4-dibromo-bpy)(CO)$_2$(PPh$_3$)$_3$]$^+$ ([Re(Br$_2$,Ph)]$^+$) and [Ru(dmb)$_2$(vpy)$_2$]$^{2+}$ ([Ru(C=C,dmb)$_2$]$^{2+}$) was performed and clearly showed that the phosphine ligands on the Re$_i$ unit were not substituted by the coupling reagents. The isolated yield of [Ru(dmb)$_2$Re(FPh)]$^{2+}$ was 25%. The isolated yield was relatively lower (8%) for [Ir(ppy)$_3$Re(Ph)]$^{2+}$, which had Ir$_n$ in both edge units, as the reaction between [Ir(C=C,ppy)]$^+$ and [Re(Br$_2$,Ph)]$^+$ was much slower than the other reactions; therefore, conversion of the starting complexes was low (Fig. S5, ESI†).

![Fig. 1](https://example.com/fig1.png)  
**Fig. 1** ESI-MS spectrum of crude products recorded after the synthesis of [Re(OEt)Re(Et)]$^{2+}$. The mobile phase was MeCN.

![Fig. 2](https://example.com/fig2.png)  
**Fig. 2** $^1$H NMR spectrum of the dinuclear complex [Re(OEt)Re(Et)]$^{2+}$. The solvent was acetone-$d_6$. The red square emphasises the peak attributed to olefinic protons.
Attempts were also made to use the Sonogashira coupling reaction to synthesise a trinuclear complex from a Ru(II) complex with an ethynyl group at the 4-position of the bpy moiety and [Re(Br2,FPh)+], as shown in eqn (3). An N,N-dimethylformamide (DMF, 5 mL) solution containing the Ru(II) complex (38 μmol), [Re(Br2,FPh)+] (19 μmol), PdCl2(PPh3)2 (0.62 μmol), CuI (2.9 μmol) and diisopropylamine (1 mL) was heated at 50 °C for 12 h under Ar. The reaction mixture was analysed by SEC and ESI-MS, which indicated that the target trinuclear complex with triple bonds between the Ru(II) and Re(I) units was successfully synthesised. Unfortunately, the trinuclear complex decomposed during the SEC purification process, most likely due to instability in the mobile phase (1 : 1 (v/v) mixture of methanol and MeCN containing 0.15 M CH3COONH4).27

As described above, the complexes that were synthesized in this research are not obtained selectively using ordinary step-wise methods because mixtures of isomers with the metals in different units are produced. Isolating the target complex from such a mixture is often difficult because of the similarities between the molecular sizes, charges, and solubility of the isomeric complexes.

**Photophysical properties of the trinuclear complexes**

As typical examples, UV-Vis absorption spectra of the synthesised trinuclear complexes [Ru(dmb)2Re(Ph)]5+, [Re(OEt)2Re(Ph)]3+ and [Irppy2Re(Ph)]3+ are shown with those of the corresponding mononuclear complexes in Fig. 3 (those of other complexes are shown in Fig. S4, ESI†). The 1MLCT absorption band of [Ru(C≡C,dmb)]2+. This was most likely caused by extension of the π conjugation in the bridging ligand, decreasing the energy level of the π* orbital.28 In addition, the molar extinction coefficient of the 1MLCT absorption band was higher for [Ru(dmb)2Re(Ph)]5+ than for the corresponding mononuclear complexes. This suggests that the transition has more π-π* character. The π-π* absorption band of [Ru(dmb)2Re(Ph)]5+ with λmax = 288 nm had a shoulder at longer wavelengths, which was not observed in the summation spectra of the corresponding mononuclear complexes (a dotted line in Fig. 3a). This shoulder can be attributed to the π-π* transition in the bridging ligand with a wide π conjugation system. In the case of [Re(OEt)2Re(Ph)]3+ (Fig. 3(b)) and [Irppy2Re(Ph)]3+ (Fig. 3(c)), similar phenomena were observed, i.e. red-shifts of both the π-π* and 1MLCT absorp-
tion bands and increase of the molar extinction coefficients of the 3MLCT absorption bands (Table 1).

All trinuclear complexes displayed emission (Fig. 4 and S5 (ESI†)). The emission for each trinuclear complex was red-shifted relative to the corresponding mononuclear complexes, and the emission quantum yield (Φem) for each trinuclear complex was much lower than those of the corresponding mononuclear complexes (Table 1).

The emission decay for each trinuclear complex could be fitted using a double exponential function (Fig. S6, ESI†). The emission lifetimes (τem) were similar to the corresponding mononuclear complexes, though the Φem were much lower; therefore, the radiative decay of the excited states of the trinuclear complexes should be slower than those of the mononuclear complexes with respect to the following equations, which show the relationships among Φem, τem and the radiative and non-radiative decay constants (k1 and kε): eqn (4) and (5).

\[
\Phi_{em} = \frac{k_1}{(k_1 + k_{\epsilon})} \quad (4)
\]

\[
\tau_{em} = \frac{1}{(k_1 + k_{\epsilon})} \quad (5)
\]

This also indicates that the lowest 3MLCT excited states of the trinuclear complexes contained higher π-π* characteristics than those of the mononuclear complexes. It has been reported that increase in π-π* character of the 3MLCT excited states of transient metal complexes induces slower radiative decay.26,29

For a more detailed investigation of the excited states of the trinuclear complexes, time-resolved emission spectra and temperature dependence of the emission decay of [Ru(dmb)2Re(Ph)]5+ were measured as a typical example. Fig. 5a shows the emission decays measured at various temperatures (243–333 K) after excitation at λex = 456 nm, where much weaker temperature dependence was observed compared to [Ru(dmb)]2+ (Fig. 5b and S7 (ESI†)). It has been reported that emission decays of many Ru(n)30 trisdiimine and Re(n)31 diimine phosphine complexes are strongly dependent on temperature, becoming faster at higher temperature due to thermal interconversion from the lowest 3MLCT excited state to the triplet ligand field excited state (1LF), which causes rapid nonradiative decay (Fig. 6). Therefore, the formation process of the 1LF should be suppressed in the case of [Ru(dmb)2Re(Ph)]5+, as the extension of π* conjugation in the bridging ligand lowers the energy level of the 3MLCT excited state. Suppression of this nonradiative decay process might be a reason for the long emission lifetime. Fig. 7a shows emission spectra recorded at various times after excitation at 456 nm. The shape of these time-resolved spectra gradually changed, as faster decay was observed at shorter wavelengths (Fig. 7b). This might be caused by intramolecular energy transfer between the Ru and Re units.

Since the trinuclear complex [Ru(dmb)2Re(Ph)]5+ has both photosensitiser (Ru) and catalyst (Re) units for CO2 reduction, it was reasonably expected that this complex could act as a photocatalyst for CO2 reduction. A mixture of DMF and triethanolamine (5:1 v/v) containing 0.05 mM [Ru(dmb)2Re(Ph)]5+ and 0.1 M 1,3-dimethyl-2-phenyl-2,3-dihydro-1H-benzo[\d]imidazole (BIIH) was irradiated at λex = 600 nm for 2 h. Selective formation of CO was observed and the turnover number (TONCO) reached 115. This TONCO was higher than that found using a Ru(n)-Re(i) dinuclear complex with a N=N–CH2–CH2–N=N bridging ligand (N=N = 4′-methyl-bpy) (TONCO = 50) under the same reaction conditions, which has been reported to be one of the most efficient supramolecular photocatalysts for the reduction of CO2 using higher-energy light such as

<table>
<thead>
<tr>
<th>Entry</th>
<th>Complex</th>
<th>λabs/nm (ε /10^4 M^-1 cm^-1)</th>
<th>λem/nm</th>
<th>Φem</th>
<th>τem /ns (A/%)</th>
<th>τr /ns (A/%)</th>
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<tr>
<td>1</td>
<td>[Re(OTe)(RePh)]+3</td>
<td>406 (31.3), 476 (sh, 20.8), 299 (65.4)</td>
<td>714c</td>
<td>0.01c</td>
<td>140 (56)c</td>
<td>771 (44)c</td>
</tr>
<tr>
<td>2</td>
<td>[Ru(bpy)2Re(Ph)]+3</td>
<td>481 (50.6), 341 (sh, 47.3), 287 (162)</td>
<td>710b</td>
<td>0.02b</td>
<td>674 (34)b</td>
<td>1424 (66)b</td>
</tr>
<tr>
<td>3</td>
<td>[Ru(dmb)2Re(Ph)]+3</td>
<td>494 (52.1), 341 (sh, 48.9), 288(150)</td>
<td>738b</td>
<td>0.02b</td>
<td>610 (18)b</td>
<td>1310 (82)b</td>
</tr>
<tr>
<td>4</td>
<td>[Ir(ppy)2Re(Ph)]+3</td>
<td>474 (14.9), 383 (35.0), 257 (120)</td>
<td>683b</td>
<td>0.01b</td>
<td>104 (82)b</td>
<td>784 (18)b</td>
</tr>
<tr>
<td>5</td>
<td>[Ru(dmb)2Re(FPh)]+3</td>
<td>495 (52.3), 341 (sh, 50.7), 287 (156)</td>
<td>743c</td>
<td>0.03c</td>
<td>471 (6)c</td>
<td>1112 (94)c</td>
</tr>
<tr>
<td>6</td>
<td>[Re(C2C6BF)]+3</td>
<td>376 (5.97), 290 (20.4)</td>
<td>635c</td>
<td>0.07c</td>
<td>326 (100)c</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>[Re(C2C6BF)]+3</td>
<td>456 (17.0), 289 (82.1)</td>
<td>636c</td>
<td>0.14c</td>
<td>1551 (100)c</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>[Ru(C2C6BF)]+3</td>
<td>462 (16.3), 288 (73.1)</td>
<td>645c</td>
<td>0.10c</td>
<td>1376 (100)c</td>
<td>—</td>
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<tr>
<td>9</td>
<td>[Ir(C2C6BF)]+3</td>
<td>384 (3.26), 314 (11.5)</td>
<td>617c</td>
<td>0.14c</td>
<td>200 (100)c</td>
<td>—</td>
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<tr>
<td>10</td>
<td>[Re(C2C6BF)]+3</td>
<td>428 (5.38), 308 (21.9)</td>
<td>647c</td>
<td>0.08c</td>
<td>1561 (100)c</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>[Re(C2C6BF)]+3</td>
<td>424 (4.29), 300 (22.2)</td>
<td>642c</td>
<td>0.07c</td>
<td>1409 (100)c</td>
<td>—</td>
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*Measured in MeCN at 25 °C. †Excitation wavelength: 456 nm. ‡Excitation wavelength: 444 nm. §Detected at each wavelength of the emission maximum.

Fig. 4 Emission spectra of [Ru(C2C6BF)]+3 (blue) and [Ru(dmb)2Re(Ph)]5+ (red) recorded in MeCN (excitation wavelength: 456 nm).
480 nm,\(^\text{10}\) because the absorption at \(\lambda = 600\) nm is stronger. Under these reaction conditions, most Ru(II) moieties should be mainly excited (Fig. 3a). After a reductive quenching process of the excited state of the Ru(II) unit by BIH, intramolecular electron transfer should proceed from the reduced Ru(II) unit to the Re(I) unit, followed by reduction of CO\(_2\) on the reduced Re(I) unit.

**Conclusions**

We successfully synthesised various trinuclear complexes from photofunctional complexes possessing vinyl or bromo groups as building blocks in a single step using the Mizoroki-Heck reaction. The obtained trinuclear complexes displayed strong absorption over a wide range of visible light and a long emission lifetime. \([\text{Ru(dmb)}_2\text{Re(Ph)}]^5^+\) functioned as a photocatalyst for CO\(_2\) reduction, even by irradiation at 600 nm.

**Experimental**

**General procedures**

\(^1\)H NMR spectra were recorded using a JEOL AL400 (400 MHz) or an AL300 (300 MHz) instrument with the analyte dissolved in acetone-\(d_6\), MeCN-\(d_3\), or CDCl\(_3\). \(^{31}\)P NMR spectra were recorded using a JEOL ECX400 (400 MHz) instrument with the analyte dissolved in acetone-\(d_6\). IR spectra were recorded using a JASCO FT/IR-610 spectrometer with a resolution of 1 cm\(^{-1}\) and with the analyte dissolved in dichloromethane. ESI mass spectrometry (MS) was performed using a Shimadzu LC-MS-2010A system, with MeCN as the mobile phase. ESI time-of-flight MS was performed using a Waters LCT Premier instrument, with MeCN as the mobile phase. Size Exclusion Chromatography (SEC) was performed using a pair of Shodex PROTEIN KW-402J columns (300 mm long, 8.0 mm i.d.) with a KW-LG guard-column (50 mm long, 6.0 mm i.d.), a JASCO 880-51 degasser, an 880-PU pump, a MD-2010 Plus UV-vis photodiode-array detector, and a Rheodyne 7125 injector. The column temperature was maintained at 40 °C using a JASCO...
860-CO oven. The eluent was a 1:1 (v/v) mixture of methanol and MeCN containing 0.5 M CH₃COONH₄, and the flow rate was 0.2 mL min⁻¹. Separation of the trinuclear complexes was achieved using SEC with a pair of Shodex PROTEIN KW-2002.5 columns (300 mm long, 20.0 mm i.d.) with a KW-LG guard column (50 mm long, 8.0 mm i.d.) and a recycling preparative HPLC apparatus with a JASCO 870-UV detector. The eluent was a 1:1 (v/v) mixture of methanol and MeCN containing 0.15 M CH₃COONH₄, and the flow rate was 6.0 mL min⁻¹. UV-vis absorption spectra were recorded using a JASCO V-670 instrument.

Emission measurements
Each compound was dissolved in MeCN and degassed using the freeze–pump–thaw method prior to measurement. Emission spectra were recorded at 25 °C using either a JASCO FP-8600 spectrofluorometer or a Hamamatsu C9920-02 system. The absolute emission quantum yields were evaluated using the Hamamatsu C9920-02 system equipped with an integrating sphere and a multichannel photodetector (PMA-12). Emission lifetimes were obtained using a HORIBA TemPro fluorescence lifetime system with an emission monochromator. The excitation light source was a NanoLED-560 pulse lamp and the instrumental response time was less than 0.1 ns. All emission decays were fitted by single or double exponential functions determined from the difference between [Ru(4,4′-dimethyl-2,2′-bipyridine)]⁺ spectra recorded with the JASCO FP-8600 spectrofluorometer and the HORIBA TemPro fluorescence lifetime system.

Photocatalytic reactions
A 4 mL aliquot of a solution in an 11 mL-cubic-quartz cell (with a light passage length of 1 cm) was irradiated with 600 nm monochromatic light obtained from a Xe lamp with a band-pass filter (FWHM = 10 nm). The incident light intensity was 4.3 × 10⁻⁸ einstein per s. The gaseous reaction products (CO and H₂) were analysed using a GC-TCD instrument (GL Science GC323). HCOOH was analysed using a capillary electrophoresis system (Otsuka Electronics Co., CAPI-3300I).

Materials
NN,N,N-Dimethylformamide (DMF) was dried over the molecular sieve 4 Å and distilled under a decreased pressure (10–20 mmHg). TEOA was distilled under a decreased pressure (<1 mmHg). The DMF and TEOA were maintained under Ar until they were used. 1,3-Dimethyl-2-phenyl-2,3-dihydro-1H-benzo[d]imidazole (BHA),¹¹ 4-methyl-4′-vinyl-2,2′-bipyridine (vbpy),¹² 4,4′-divinyl-2,2′-bipyridine (dvbpy),¹³ Ru(N=NC₂H₅)(N=backpy or dmb),¹⁴ [Ru(C≡C,py)]¹⁵,¹⁶, [Ru(C≡C,dmb)]²⁴,²⁵ [Ir(C≡C,ppy)]²⁶, and 4′-bromo-2,2′-bipyridine,²⁷–²⁹ Re-(CO)₃Br⁴⁰ were prepared according to the reported methods with some modifications. All of the other reagents were of reagent grade quality and were used without further purification.

Synthesis
Re(i) complexes. Re(P₄Et₃)₂Cl₂Br. Re(CO)₃Br (457.9 mg, 1.127 mmol) and P₄Et₃ ethanol solution (20 wt%, 1.63 g, 2.759 mmol) were dissolved in toluene (60 mL, degassed using Ar) and refluxed under Ar for 12 days. After removing the solvent under a decreased pressure, white solids were obtained, which were recrystallized with MeOH/water, washed with water, and then dried under vacuum. Yield: 203.7 mg (30.9%). FT-IR (in CH₂Cl₂ ν/cm⁻¹: 2044, 1940, 1888. ¹H NMR (297.60 MHz, acetone-d₆): δ/ppm, 2.12–2.02 (m, 12H, P(CH₂CH₃)₃), 1.16–1.06 (m, 18H, P(CH₂CH₃)₃).

Re(Br,bpy)(CO)₃(P₄Et₃)²⁺(PF₆)²⁺ [Re(Br,bpy)(CO)₃(P₄Et₃)²⁺(PF₆)²⁺]. Re(P₄Et₃)₃(CO)Br (100.0 mg, 0.1705 mmol) and silver triflate (48.5 mg, 0.212 mmol) were dissolved in toluene (15 mL) and heated at 90 °C under Ar overnight. Brbpy (39.2 mg, 0.166 mmol) was added to the reaction mixture and heated overnight. After a second addition of Brbpy (55.6 mg, 0.233 mmol), the solution was further heated for 1 d. The solvent was evaporated to give an orange-red residue, which was purified by flash column chromatography on silica gel (collected as the second fraction using 100:0–100:5 (v/v) CH₂Cl₂/MeOH as the eluent). The obtained orange-red solid was dissolved in MeOH to which a saturated methanol solution of NH₄PF₆ and a small amount of water were added. The solution was gradually evaporated until the orange-red solid precipitated. The solid was washed with water and Et₂O and dried at 60 °C under vacuum. Yield: 112.8 mg (77.0%, over 2 steps). ESI-MS (in MeCN) m/z: 713 ([M – PF₆]⁺). FT-IR (in CH₂Cl₂ ν/cm⁻¹: 1934, 1864. ¹H NMR (297.60 MHz, acetone-d₆): δ/ppm, 9.32 (d, J = 5.4 Hz, 1H, Brbpy-6), 9.14 (d, J = 6.0 Hz, 2H, Brbpy-6’), 9.02 (d, J = 2.2 Hz, 1H, Brbpy-3’), 8.90 (dd, J = 1.4, 8.2 Hz, 1H, Brbpy-3), 8.38 (dd, J = 6.9, 8.2 Hz, 1H, Brbpy-4), 8.03 (dd, J = 2.2, 6.0 Hz, 1H, Brbpy-5’), 7.89 (ddd, J = 1.4, 5.4, 6.9 Hz, 1H, Brbpy-5), 1.59–1.52 (m, 12H, P(CH₂CH₃)₃), 0.92–0.83 (m, 18H, P(CH₂CH₃)₃). Elemental Anal. Calcd for C₂₆H₂₃BrF₆N₂O₂P₃Re: C, 33.57; H, 4.34; N, 3.26. Found: C, 33.94; H, 4.18; N, 3.30.

Re[P(OEt)₃]₃(CO)Br. Re(CO)₃Br (1.17 g, 2.89 mmol) and P(OEt)₃ (1.13 g, 6.82 mmol) were dissolved in toluene (100 mL) and the solution was refluxed under Ar for 28 h. After the solvent was evaporated, the residue was separated by column chromatography on alumina (collected as a first fraction, using 100:0–0:100 (v/v) CH₂Cl₂/hexane as the eluents). The obtained white solids were dried under vacuum. Yield:
1.37 g (69.8%). FT-IR (in CH₂Cl₂) ν_{CO}/cm⁻¹: 2069, 2048, 1970, 1920. ¹H NMR (297.60 MHz, acetonitrile-d₆): δ/ppm, 4.19–4.10 (m, 12H, P(OCR₂CH₂CH₃)₁₃), 1.31 (t, J = 6.9 Hz, 18H, P(OCR₂CH₂CH₃)₁₃). Re[BP₃(PO₃CH₃)₃]PF₆ (201.0 mg, 0.3077 mmol) and silver triflate (68.65 mg, 0.3433 mmol) were dissolved in THF (20 mL), and the solution was refluxed under Ar for 4 h. Precipitated AgBr was filtered by Celite. A brown oil was collected after the solvent was evaporated. Toluene (25 mL) containing the oil and 4-methyl-4′-vinyl-2,2′-bipyridine (vpb, 72.3 mg, 0.368 mmol) was heated at 90 °C under Ar for 21.5 h. Evaporation of the solvent gave a brown residue, which was separated by flash column chromatography on silica gel (collected as a first yellow fraction, using 100:0–100:2 (v/v) CH₂Cl₂/MeOH as the eluent). The obtained white solids were recrystallized with toluene–hexane, and dried under vacuum. Yield: 155 mg (61.8%). FT-IR (in CH₂Cl₂) ν_{CO}/cm⁻¹: 2057, 1955, 1911. ¹H NMR (399.65 MHz, acetone-d₆) δ/ppm, 7.69–7.75 (m, 18H, m-Ph), 7.26 (dd, J = 8.8, 8.8 Hz, 18H, o-Ph). Elemental Anal. Calcd for C₁₉H₁₃BrF₆O₃P₂Re: C, 47.67; H, 2.46. Found: C, 47.84; H, 2.70.

Re{P[F(C₆H₄)]₃}PF₆. Re{P[F(C₆H₄)]₃}Br (104 mg, 0.255 mmol) and P{P[F(C₆H₄)]₃}Br (165 mg, 0.522 mmol) were dissolved in toluene (20 mL), and the solution was refluxed under N₂ for 23 h. Evaporation of the solvent gave a yellow oil which was separated by column chromatography on silica gel (eluent: CH₂Cl₂). The obtained white solids were recrystallized with toluene–hexane, and dried under vacuum. Yield: 155 mg (61.8%). FT-IR (in CH₂Cl₂) ν_{CO}/cm⁻¹: 2057, 1955, 1911. ¹H NMR (399.65 MHz, acetone-d₆) δ/ppm, 7.69–7.75 (m, 18H, m-Ph), 7.26 (dd, J = 8.8, 8.8 Hz, 18H, o-Ph). Elemental Anal. Calcd for C₁₉H₁₃BrF₆O₃P₂Re: C, 47.67; H, 2.46. Found: C, 47.84; H, 2.70.

[Re{BP₃}₃]PF₆. [Re{BP₃}₃]Br (298.6 mg, 0.3414 mmol) and silver triflate (105.0 mg, 0.315 mmol) and silver triflate (92.5 mg, 0.359 mmol) were dissolved in THF (30 mL), and the solution was refluxed under Ar for 3 h. Precipitated AgBr was filtered by Celite. White solids were collected after the solvent was evaporated. The toluene solution (30 mL) containing the obtained residue and 4,4′-dibromo-2,2′-bipyridine (Br₂bp, 119 mg, 0.380 mmol) was heated at 90 °C under N₂ for 16 h. After the solvent was evaporated, the obtained orange solids were purified by flash column chromatography on silica gel (collected as the first orange fraction, using 100:0–100:5 (v/v) CH₂Cl₂/MeOH as the eluents). The purification method was the same as that for [Re{BP₃}₃]PF₆. Yield: 333 mg (79.2%). ESI-MS (in MeCN) m/z: 1189 ([Re{BP₃}₃]PF₆[Re{BP₃}₃]Br)PF₆). FT-IR (in CH₂Cl₂) ν_{CO}/cm⁻¹: 1943, 1874. ¹H NMR (297.60 MHz, acetone-d₆): δ/ppm, 8.72 (d, J = 1.8 Hz, 2H, Br₂bp-3',3’), 8.13 (d, J = 6.0 Hz, 2H, Br₂bp-6',6”) 7.46–7.38 (m, 14H, bpy-5,5’–bpy-7,7’), 7.14 (dd, J = 8.7, 8.7 Hz, 12 H, o-Ph). Elemental Anal. Calcd for C₁₉H₁₃BrF₆N₂O₃P₂Re: C, 47.03; H, 2.96; N, 2.29. Found: C, 46.95; H, 3.03; N, 2.15.

[Re{BP₃}₃]PF₆. [Re{BP₃}₃]Br (298.6 mg, 0.3414 mmol) and silver triflate (105.0 mg, 0.4087 mmol) were dissolved in CH₂Cl₂ (30 mL) and the solution was refluxed under N₂ for 17 h. Precipitated AgBr was filtered by Celite. After evaporating the solvent, the obtained white residue and 4,4′-dibromo-2,2′-bipyridine (Br₂bp, 129.4 mg, 0.4120 mmol) were dissolved in toluene (30 mL, degassed using N₂), and the solution was heated at 90 °C under N₂ for 16 h. The orange precipitate was filtered off, washed with toluene and hexane, and purified by flash column chromatography on silica gel (collected as a first orange fraction, using 100:0–100:5 (v/v) CH₂Cl₂/MeOH as the eluents). The purification method was the same as that for [Re{BP₃}₃]PF₆. Yield: 321.7 mg (76.9%). ESI-MS (in MeCN) m/z: 1081 ([M – PF₆]⁺). FT-IR (in CH₂Cl₂) ν_{CO}/cm⁻¹: 1942, 1874. ¹H NMR (297.60 MHz, acetone-d₆): δ/ppm, 8.15 (d, J = 1.8 Hz, 2H, bpy-3,3’), 7.65 (d, J = 6.0 Hz, 2H, bpy-6,6’), 7.16–7.30 (m, 30H, 2PPh₃), 6.84 (dd, J = 1.8, 6.0 Hz, 2H, bpy-5,5’). Elemental Anal. Calcd for C₁₉H₁₃BrF₆N₂O₃P₂Re: C, 47.03; H, 2.96; N, 2.29. Found: C, 46.95; H, 3.03; N, 2.15.

[Re{dVbpy}₃]PF₆. [Re{C₄₂H₃2F₆N₂O₃P₂Re}₃]PF₆ ([C₄₂H₃2F₆N₂O₃P₂Re]•) was synthesized by a method similar to that for the synthesis of [Re{BP₃}₃]PF₆ using dVbpy instead of Br₂bp, yield: 56.4%. ESI-MS (in MeCN) m/z: 975 ([M – PF₆]⁺). FT-IR (in CH₂Cl₂) ν_{CO}/cm⁻¹: 1937, 1867. ¹H NMR (297.60 MHz, acetone-d₆): δ/ppm, 8.49 (d, J = 1.6 Hz, 2H, bpy-3,3’), 7.98 (d, J = 5.8 Hz, 2H, bpy-6,6’), 7.16–7.30 (m, 30H, 2PPh₃), 7.06 (dd, J = 1.6, 5.8 Hz, 2H, bpy-5,5’), 6.81 (dd, J = 10.6, 17.4 Hz, 2H, −CH=CH₂), 6.27 (d, J = 10.6 Hz, 2H, −CH=CH₂ (cis), 5.73 (d, J = 17.4 Hz, 2H, −CH=CH₂ (trans)). ³¹P NMR (400 MHz, acetone-d₆): δ/ppm, 21.9 (s, 2P, PPh₃), 143.6 (7, 1P, PF₆). HRMS (ESI-TOF) m/z: [M – PF₆]⁺. Calculated for C₈₂H₃₄F₆N₂O₆P₁₀Re: 2364.9820; Found: 2364.0915.
Synthesis of multinuclear complexes using the Heck reaction.

\[[\text{Re}(\text{OEt})_{2}\text{Re}(\text{Ph})][\text{PF}_{6}]_3, \ [\text{Re}(\text{Br}_2\text{Ph})][\text{PF}_{6}] \ (10 \text{ mg, 0.0081 mmol}), \ [\text{Re}(\text{C}==\text{C} \text{OEt})][\text{PF}_{6}] \ (15 \text{ mg, 0.016 mmol}), \ \text{Pd(OAc)}_2 \ (0.37 \text{ mmol, 0.0032 mmol}) \text{ and AcONa (3.3 mmol, 0.041 mmol) were dissolved in MeCN degassed using Ar (4 \text{ mL}). The solution was refluxed at 75 \degree C under N}_2 for 2 days in dim light. An MeCN solution (2 \text{ mL}) containing Pd(OAc)_2 (0.37 mmol, 0.0016 mmol) and PPh_3 (0.85 mmol, 0.0032 mmol) was added and refluxed 2 days again. Evaporation of the solvent gave brown solids, which were purified twice by ion-exchange chromatography (SP Sephadex C-25) and water containing NH_4PF_6 (0–8 \text{ mm})). The solvent was evaporated until solids were precipitated. The solid was washed with water and Et_2O, and then dried at 60 \degree C under vacuum. Yield: 7.4 mg (31%).]

1H NMR (400 MHz, acetone-d_6): \(\delta\) ppm, 9.11 (d, \(J = 5.8 \text{ Hz}, 2\text{H}, \beta\)-py, 8.97 (d, \(J = 5.2 \text{ Hz}, 2\text{H}, \alpha\)-py, 8.92 (s, 2\text{H}, \beta\)-py, 8.71 (s, 2\text{H}, \gamma\)-py, 8.57 (s, 2\text{H}, \gamma\)-py, 8.13 (d, \(J = 5.2 \text{ Hz}, 2\text{H}, \gamma\)-py, 8.03 (d, \(J = 5.8 \text{ Hz}, 1\text{H}, \beta\)-py), 7.93 (d, \(J = 5.2 \text{ Hz}, 2\text{H}, \gamma\)-py), 7.72 (d, \(J = 5.2 \text{ Hz}, 2\text{H}, \alpha\)-py), 7.42–7.28 (m, 34\text{H}, –CH=CH, 2\text{PPh}_3, 3.95–3.88 (m, 24\text{H}, 4\text{P(OCH}_2\text{C}_6\text{H}_4\text{O})_3\text{PF}_6\), 2.74 (s, 6\text{H}, \alpha\)-py-CH_3), 1.08 (t, \(J = 7.1 \text{ Hz}, 36\text{H}, 4\text{P(OCH}_2\text{C}_6\text{H}_4\text{O})_3\text{PF}_6\)). FT-IR (in CH_2Cl_2) \(\nu\) cm\(^{-1}\): 1954, 1930, 1870, 1860. ESI-MS (in MeCN) \(m/z\): 210 (M–3PF_6)^{3+}, 1303 (M–2PF_6)^{3+}. HRMS (ESI-TOF) \(m/z\): M+ Caled: 1501.0327; Found: 1501.0326.

1H NMR (400 MHz, acetone-d_6): \(\delta\) ppm, 7.18 (d, \(J = 5.8 \text{ Hz}, 2\text{H}, \gamma\)-py, 8.34 (d, \(J = 5.8 \text{ Hz}, 2\text{H}, \alpha\)-py, 8.93 (s, 2\text{H}, \beta\)-py, 8.87 (d, \(J = 7.1 \text{ Hz}, \gamma\)-py), 8.76 (s, 2\text{H}, \gamma\)-py, 8.37 (d, \(J = 7.1 \text{ Hz}, \delta\)-py), 8.07 (m, 2\text{H}, –CH=CH, 7.80 (m, 2\text{H}, \beta\)-py, 7.77 (d, \(J = 5.8 \text{ Hz}, 1\text{H}, \gamma\)-py), 7.68 (d, \(J = 7.1 \text{ Hz}, 1\text{H}, \alpha\)-py, 7.39–7.36 (m, 12\text{H}, P(OCH}_2\text{C}_6\text{H}_4\text{O})_3\text{PF}_6\), 2.67 (s, 3\text{H}, \beta\)-py-CH_3), 1.60–1.53 (m, 12\text{H}, P(OCH}_2\text{C}_6\text{H}_4\text{O})_3\text{PF}_6\)). 31P NMR (400 MHz, acetone-d_6): \(\delta\) ppm, 117.0 (s, 4\text{P}, \beta\)-py, 8.94 (s, 4\text{P}, \gamma\)-py, 117.0 (s, 2\text{P}, P(OEt)_3), –2.06 (s, 2\text{P}, PhP), –143.5 (7, 2\text{P}, PF_6\)). FT-IR (in CH_2Cl_2) \(\nu\) cm\(^{-1}\): 1930, 1880, 1860. ESI-MS (in MeCN) \(m/z\): 702 (M–2PF_6)^{3+}. Elemental Anal. Caled for C_{55}H_{78}F_3O_2P_7Re_3: C, 46.17; H, 6.46; N, 3.31. Found: C, 36.05; H, 4.30; N, 3.33. HRMS (ESI-TOF) \(m/z\): [M – PF_6]^2+. Caled for C_{51}H_{52}N_4O_4P_2Re_3 701.1879; Found: 701.1848.
and a small amount of water were added to the solution. After evaporation of methanol, the obtained orange solids were collected, washed with water and EtO, and dried at 60 °C under vacuum. Yield: 2.0 mg (8.0%).1H NMR (400 MHz, acetone-6): δ/ppm, 9.01 (s, 2H,  β-ppy-3), 8.71 (s, 2H,  α-ppy-3), 8.66 (s, 8H, dmb-3,3′), 8.56 (s, 2H,  γ-ppy-3), 8.18 (d, J = 6.0 Hz, 2H, γ-ppy-6), 8.08 (d, J = 6.0 Hz, 2H, β-ppy-6), 7.96 (d, J = 5.6 Hz, 2H, γ-ppy-5), 7.86–7.82 (m, 12H, dmb-6,6′), −CH2CH=−), 7.69 (d, J = 5.6 Hz, 2H, α-ppy), 7.46–7.38 (m, 24H, α-ppy-5, β-ppy-5, dmb-5,5′, m-Ph), 7.13–7.09 (m, 12 H, o-Ph), 2.63 (s, 3H, α-Ch3), 2.56 (s, 24H, dmb-Ch3).31P NMR (400 MHz, acetone-6): δ/ppm, 21.7 (s, 2P, −PPh3), −143.5 (7, 5P, PF6). FT-IR (in CH2Cl2) v/cm−1: 1932, 1820. ESIMS (in MeCN) m/z: 472 [M − 5PF6]3+), 626 [M − 4PF6]4+), 883 [M − 3PF6]5+). HRMS (ESI-TOF) m/z: [M − 5PF6]3+ Calcd for C122H100F12N14O2P3ReRu2 847.1550; Found: 847.1474.


Notes and references

25 Rigorously excluding air contamination in the reaction vessel dramatically decreased the yield of [Re(OEt)Re(Et)]²⁺. However, adding too much air to the reaction vessel also decreased the yield. Air contamination that occurred when the cap of the vessel was opened to allow the reagents to be added supplied a suitable amount of air for [Re(OEt)-Re(Et)]²⁺ to be produced. The role of air in the reaction is currently being investigated in our laboratory.
27 Various decomposition products, including several kinds of mononuclear, dinuclear, and other kinds of trinuclear complexes, were observed.