Potential host compounds: 1,1′-bis(diarylhydroxymethyl)ferrocenes

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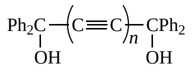
1,1′-Bis(hydroxydiphenylmethyl)- 9a, *rac*-1,1′-bis(1-hydroxy-1-phenylethyl)- 9b, *rac*-1,1′-bis(*o*-chlorophenylphenylhydroxymethyl)- 9c and *rac*-1,1′-bis(hydroxy-1-naphthylphenylmethyl)-ferrocene 9d were prepared as host compounds. X-Ray crystal structures of 1:1 inclusion complexes of 9a with MeOH and of 9b with dimethylformamide, and 9c itself were analysed.

It has been postulated that organic molecules with a rigid structure and possessing a diarylhydroxymethyl group will act as host compounds to include various guests.[1] Such alcoholic host compounds aggregate to some degree through the formation of a hydrogen bond network because of their sterically crowded hydroxy groups. Some host compounds bearing the diarylhydroxymethyl group such as **1a**,[2] **1b**[2] and **1c**[3] have been found to work as good host compounds. Similarly **2** and **3** have been designed as good hosts.[4] Chiral host compounds, **4**, **5a** and derivatives **5b** and **5c** have been used as hosts in enantiomer resolution and enantioselective reactions of guests.[5] By using the triple bond as a rigid skeleton together with the diarylhydroxymethyl group, the interesting sexipedal host, **6a**[6] and its chiral derivative, **6b**[7] have been prepared and their high inclusion tendencies studied.



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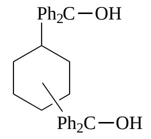
a: $n = 2$
b: $n = 1$
c: $n = 0$



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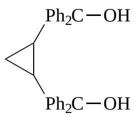

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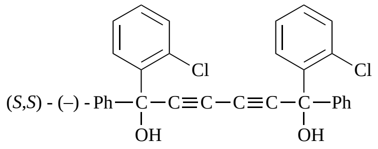

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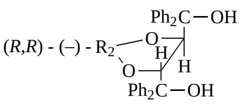

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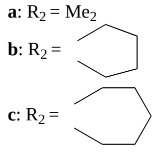

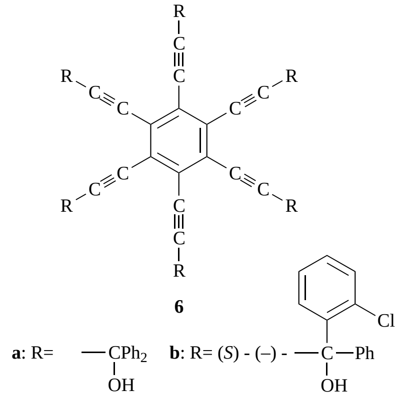

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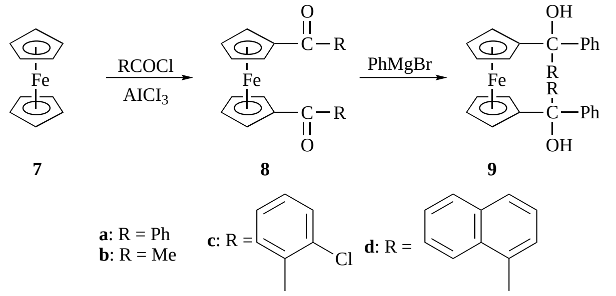
We now have designed a new host compound which contains ferrocene as the rigid skeleton and the diarylhydroxymethyl group. We expected that the ferrocene host would show high inclusion ability for various guests since the host molecule can rotate freely around the bond binding the two cyclopentadiene rings to optimise hydrogen bonding between host and guest.

1,1-Bis(hydroxydiphenylmethyl)ferrocene **9a** was prepared as red prisms by a Grignard reaction of PhMgBr with 1,1′-dibenzoylferrocene **8a** (prepared by a benzoylation of ferrocene **7**) (Scheme 1). By a similar Grignard reaction with PhMgBr, *rac*-1,1′-bis(1-hydroxy-1-phenylethyl)- **9b**, *rac*-1,1′-bis(*ortho*-chlorophenylphenylhydroxymethyl)- **9c** and *rac*-1,1′-bis-(hydroxy-1-naphthylphenylmethyl)-ferrocene **9d** were prepared from 1,1′-diacetyl- **8b**, 1,1′-di(*ortho*-chlorobenzoyl)- **8c** and 1,1′-di(1-naphthoyl)-ferrocene **8d**, respectively. In all cases, only *rac*-derivatives and no *meso*-isomers were produced. In the Grignard reaction, a kinetic mechanism to produce *rac*-isomer selectively is invoked, such as formation of an intramolecularly Mg-bridged intermediate between the two C=O groups, C=O · · · MgBr$^+$ · · · O=C. PhMgBr reagents then attack the C=O groups from the direction which produces the *rac*-product only. The *rac*-structure of **9b–c** was elucidated by X-ray analysis.



Scheme 1

Inclusion tendencies of the hosts **9a–d** were tested for several typical guest compounds and are summarized in Table 1. Although **9a** and **9d** showed relatively high inclusion ability, **9b** and **9c** showed poor inclusion ability (Table 1). In general, the inclusion ability of *rac*-host is lower than that of optically active host. Thus, **9b** and **9c** should be poor hosts, although *rac*-**9d** showed quite high inclusion ability. In order to clarify the reason for this, X-ray crystal structures of the 1:1 MeOH complex of **9a**, 1:1 DMF (dimethylformamide) complex of **9b** and the host **9c** itself were studied.

The molecular structure of the 1:1 complex of **9a** and MeOH is shown in Fig. 1. The host, **9a** has a non-

Table 1 Host–guest ratio[a] (H : G) and melting point of inclusion complexes of ferrocene hosts **9a–d** with typical guest compounds

	Host							
	9a		**9b**		**9c**		**9d**	
	H:G	Mp/°C	H:G	Mp/°C	H:G	Mp/°C	H:G	Mp/°C
MeOH	1:1	163–165	—		—			
EtOH	1:1	156–158	—		—			
THF	—		—		—		1:2	160–164
Dioxane	—		—		—		1:2	150–154
Acetone	—		—		—		1:1	142–144
Pyridine	1:2	117–120	—		1:2	180–182	1:1	165–170
DMF	2:1	138–140	1:1	76–78	—		1:1	126–128
Me_2SO	1:2	152–155	—		1:2	142–145	1:2	164–168

[a] The host–guest ratio was determined by thermogravimetry and ^1H NMR spectroscopy.

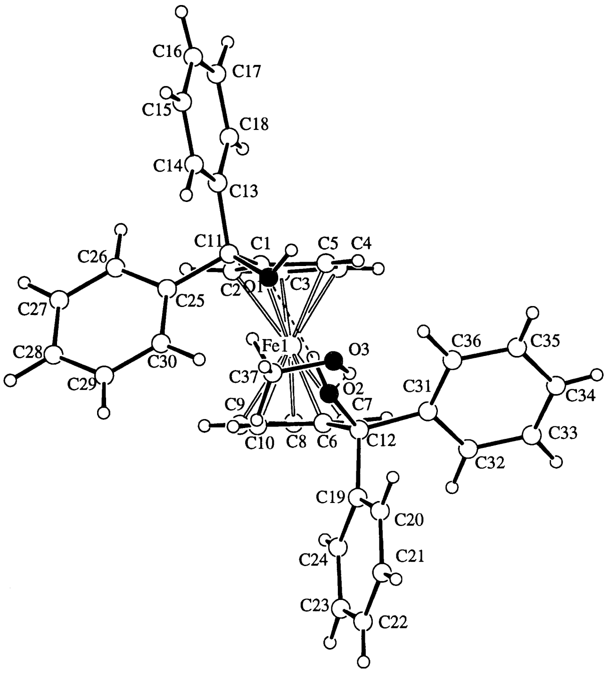


Fig. 1 Molecular structure of **9a**·MeOH

crystallographic twofold axis which goes through Fe1. An intramolecular hydrogen bond is formed between O1 as an acceptor and O2 as a donor [O2–H ··· O1 = 2.774(2) Å and ∠O2–H ··· O1 = 153.4°], resulting in concentration of hydrophilic groups on the centre of the molecule, surrounded by large hydrophobic substituents on C11 and C12. The two cyclopentadienyl rings of **9a** are in an almost eclipsed form, and are not parallel, having an interplanar angle of 5.1°, because of the steric congestion of bulky substituents on C11 and C12: the intramolecular distances of C1 ··· C10, C5 ··· C6 and C3 ··· C8 are 3.375, 3.391 and 3.191 Å, respectively. The orientation of the four benzene rings is determined mainly by formation of the intramolecular hydrogen bond and the interactions between the ferrocene moiety and the phenyl rings. The dihedral angles of C1–C11–C13–C18, C6–C12–C19–C24, C1–C11–C25–C26 and C6–C12–C31–C32 are 5.9, 12.8, −73.7 and −69.0°, respectively.

The crystal structure of **9a**·MeOH is shown in Fig. 2. Two MeOH molecules as guests are located around a centre of symmetry and bridge the two host molecules of **9a** by cyclic hydrogen bonding (O2–H ··· O1–H ··· O3–H ··· O2′–H ··· O1′–H ··· O3′–H ··· O2) to give a dimer-like structure. The distances and angles of intermolecular hydrogen bonds are 2.760(3) and 2.803(2) Å, and 167.3 and 144.2° for O1–H ··· O3 and O3–H ··· O2′, respectively. The dimers with hydrophilic interiors and hydrophobic exteriors stack along the *c*-axis to make an inclusion column.

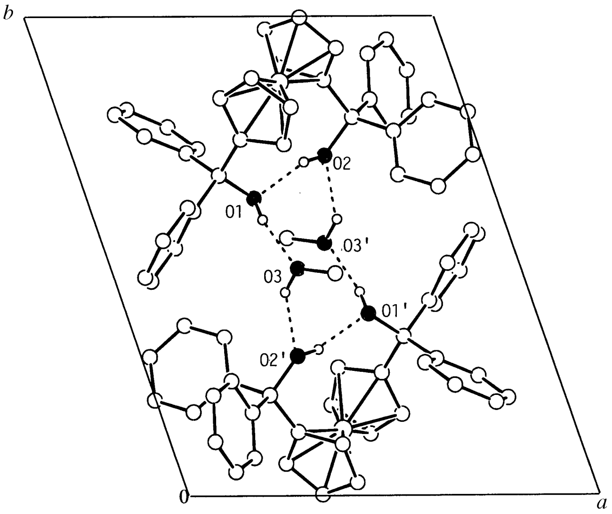


Fig. 2 Crystal structure of **9a**·MeOH

The molecular structure of the 1:1 complex of **9b** with DMF is shown in Fig. 3. The host, **9b**, has a non-crystallographic twofold axis which goes through Fe1. An intramolecular hydrogen bond is formed between O1 and O2 with O2–H ··· O1 = 2.921(3) Å and ∠O2–H ··· O1 = 171.8°. Two cyclopentadienyl rings of **9b** are nearly eclipsed and make an angle of 2.44° to each other, the distances of C1 ··· C10, C5 ··· C6 and C3 ··· C8 being 3.35, 3.31 and 3.25 Å, respectively. Thus, the overall structure of **9b** is similar to that of **9a**, although the hydroxydiphenylmethyl groups of **9a** on C11 and C19 are replaced by 1-hydroxy-1-phenylethyl groups in **9b** and the orientations of the phenyl groups are different between **9a** and **9b** (see Figs. 1 and 3). The dihedral angles of C1–C11–C13–C14 and C6–C19–C21–C22 are −94.2 and −100.2°, in contrast to the corresponding values of 5.9 and 12.8° in **9a**. The hydroxy group (O1–H) of **9b** is hydrogen bonded to the carbonyl oxygen of DMF and the hydrogen bond distance and angle are 2.779(3) Å and 170.4°.

The crystal structure of **9b**·DMF is shown in Fig. 4. The host molecules stack along the *a*-axis to form an inclusion column, in the centre of which the guest molecules, DMF, are included. The interior of the column consists of the hydrophilic site of **9b** as hydrogen bond donors to the guests and hydrophobic moieties, interacting with the methyl groups of the guests.

The molecular structure of **9c** is shown in Fig. 5. The molecule, **9c**, has a non-crystallographic twofold axis which goes through Fe1. An intramolecular hydrogen bond is formed between O1 and O2 [O2–H ··· O1 = 2.860(3) Å and ∠O2–H ··· O1 = 169.8°] and between O1 and Cl1 [O1–H ··· Cl1 = 3.072(3) Å and ∠O1–H ··· Cl = 136.0°]. The two cyclopentadienyl rings of **9c** are in the eclipsed conformation and make an angle of

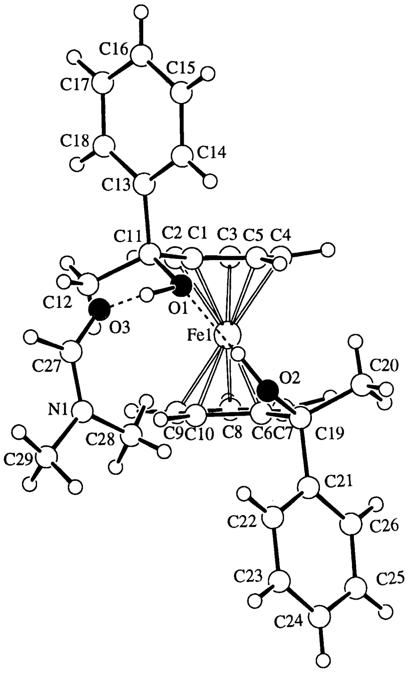


Fig. 3 Molecular structure of **9b**·DMF

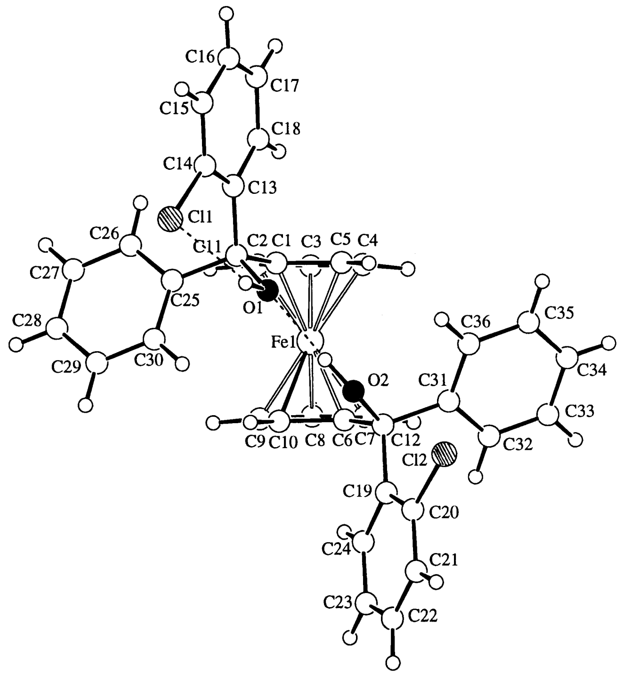


Fig. 5 Molecular structure of **9c**

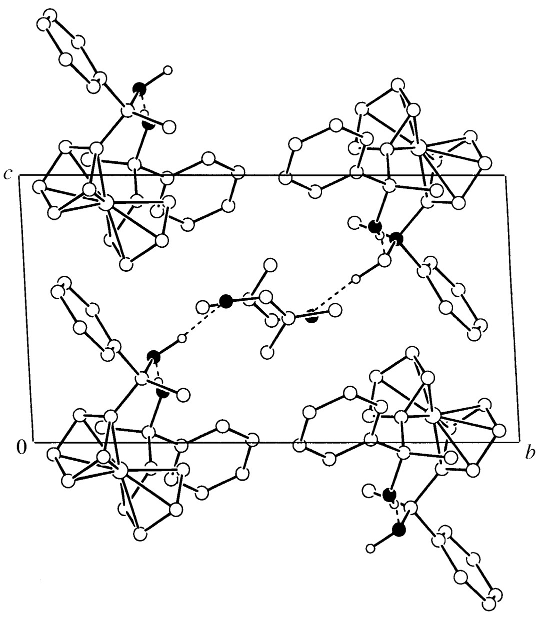


Fig. 4 Crystal structure of **9b**·DMF

4.5° to each other, the bond distances of C1 · · · C10, C5 · · · C6 and C3 · · · C8 being 3.389, 3.370 and 3.213 Å, respectively. The orientation of the phenyl rings on C11 and C12 is characterized by the following dihedral angles; C1–C11–C13–C18 = 7.5°, C6–C12–C19–C24 = 7.7°, C1–C11–C25–C26 = −78.0° and C6–C12–C31–C32 = −73.0°. These geometrical parameters clearly show that the overall structure of **9c** is quite similar to that of **9a** (see Figs. 1 and 5). Since the two hydroxy groups of **9c** are involved in intramolecular hydrogen bonds and the two chlorine atoms at C14 and C20 partially cover the hydrophilic centre of **9c**, the molecule **9c** might have low ability to form an inclusion complex with the guest molecules.

Conclusion

The molecules of **9a–c** were designed as host molecules, to form complexes with various guest molecules, by use of the formation of hydrogen bonds between the hydrophilic centres of hosts and hydrophilic sites of guest molecules and the interactions between the hydrophobic substituents of hosts and hydrophobic moieties of guest molecules. However, these hosts formed complexes with a very limited number of guest compounds, as described above, which might in part be due to the hardness of the host molecules. The molecules of **9a–c** have near C_2 symmetry in spite of a lack of C_2 symmetry in molecular assemblies in the crystals, reflecting that the molecules may not be so flexible to adjust their conformation to the guest molecule.

Experimental

^{1}H NMR and IR spectra were measured on a JNM-LA300 FT spectrometer for $CDCl_3$ solutions and on a FT/IR-300 JASCO spectrometer for Nujol mulls, respectively.

Preparation of 1,1′-diaryloyl- and 1,1′-diacetyl-ferrocenes

According to the reported benzoylation[8] and acetylation[9] procedure of **7** by using $AlCl_3$ in CH_2Cl_2, **8a** as red prisms (83% yield, mp 104–105 °C; lit.,[8] 106.5–106.7 °C) and **8b** as ruby-red plates (80% yield, mp 124–125 °C; lit.,[9] 127.5–128.5 °C) were prepared, respectively. Their IR spectral data are identical to those reported. By a similar aryloylation reaction of **7** with *ortho*-chlorobenzoyl chloride and 1-naphthoyl chloride, **8c** as red prisms (82% yield, mp 166–168 °C) and **8d** as orange prisms (62% yield, mp 145–148 °C) were also prepared.

Preparation of 1,1′-bis(diarylhydroxymethyl)- and 1,1′-bis(1-hydroxy-1-phenylethyl)-ferrocenes

To a solution of PhMgBr prepared from Mg (1.94 g, 0.08 g atom) and PhBr (13.3 g, 0.085 mol) in diethyl ether (50 ml), was added a solution of **8a** (7.9 g, 0.08 mol) in diethyl ether (300 ml), and the mixture was heated under reflux for 6 h. The reaction mixture was decomposed with dilute HCl solution and extracted with toluene. The toluene solution was washed (water and aqueous $NaHCO_3$) and dried (Na_2SO_4). Evaporation of the solvent of the toluene solution gave, after recrystallization from EtOH, **9a** as orange prisms, 8.6 g, 77.5% yield, mp 179–181 °C, ν/cm^{-1} 3338 (OH), δ_H 3.95 and 4.16 (each t, 4 H, cyclopentadiene), 4.06 (s, 2 H, OH) and 7.30 (m, 20 H, Ph). Anal. Calc. for $C_{36}H_{30}O_2Fe$: C, 78.55; H, 5.49%. Found: C, 78.64; C, 5.40%.

By a similar Grignard reaction of **8b** with PhMgBr, **9b** was obtained as orange needles, 65% yield, mp 143–144 °C, ν/cm^{-1} 3356 (OH), δ_H 1.88 (s, 6 H, Me), 4.02 (s, 2 H, OH), 4.22 (t, 4 H, cyclopentadiene), 4.27 and 4.34 (each q, 2 H, cyclopentadiene) and 7.30 (m, 20 H, Ph). Anal. Calc. for $C_{26}H_{26}O_2Fe$: C, 73.25; H, 6.15%. Found: C, 73.29; H, 6.15%. The cyclopentadiene ring proton signals of ferrocene derivatives which are substituted with phenyl or naphthyl group are complicated by an anisotropy effect of the aromatic ring.[10] When the cyclopentadiene ring is substituted with a chiral group, its proton signals are more complicated due to a chiral effect.

By a similar Grignard reaction of **8c** with PhMgBr, **9c** was obtained as orange prisms, 26% yield, mp 211–213 °C, ν/cm^{-1} 3558 (OH), δ_H 3.63, 3.79, 4.10 and 4.75 (each t, 2 H, cyclopentadiene), 5.34 (s, 2 H, OH) and 7.05–7.39 (m, 10 H, Ph). Anal. Calc. for $C_{36}H_{28}O_2Cl_2Fe$: C, 69.81; H, 4.56%. Found: C, 69.88; H, 4.51%.

By a similar Grignard reaction of **8d** with PhMgBr, **9d** was obtained as orange prisms, 29% yield, mp 209–211 °C, ν/cm^{-1} 3518 and 3442 (OH); δ_H 3.70, 3.83, 4.15 and 4.78 (each s, 2 H, cyclopentadiene), 4.73 (s, 2 H, OH), 6.99 (d, 2 H, Ph), 7.24 (m, 12 H, Ph), 7.50 (d, 4 H, Ph), 7.76 (t, 4 H, Ph) and 8.07 (d, 2 H, Ph). Anal. Calc. for $C_{44}H_{34}O_2Fe$: C, 81.23; H, 5.27%. Found: C, 81.19; H, 5.25%.

X-Ray analysis

The single crystals suitable for X-ray analyses were obtained by recrystallization from MeOH for the 1:1 MeOH complex of **9a**, from DMF for the 1:1 DMF complex of **9b**, and from MeCN for **9c**. All data were collected on a Rigaku AFC7R four-circle diffractometer with graphite monochromated Cu-Kα radiation using the ω–2θ scan technique and a rotating anode generator (50 kV, 200 mA). The structures were solved using direct methods.[11] The non-hydrogen atoms were refined anisotropically and all hydrogen atoms were included in the structure factor calculations. Empirical absorption corrections were applied.[12] All calculations were performed using the TEXSAN crystallographic software package.[13]

Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see ‘Instructions for Authors’, *J. Chem. Soc., Perkin Trans. 2*, 1997, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 188/43.

Crystal data for 9a·CH_3OH

$C_{37}H_{34}O_3Fe$, $M = 582.52$. Triclinic, $a = 12.273(1)$, $b = 14.864(1)$, $c = 8.753(1)$ Å, $\alpha = 97.91(1)$, $\beta = 100.85(1)$, and $\gamma = 106.58(1)°$, $U = 1471.7(2)$ Å^3, space group $P1$, $Z = 2$, $D_c = 1.314$ g cm^{-3}. Orange, prismatic crystal. Crystal dimensions 0.26 × 0.18 × 0.17 mm, μ(Cu-Kα) = 43.85 cm^{-1}. 4384 unique reflections ($2\theta < 120.1°$), 4196 with $I > 2\sigma(I)$, transmission factors: 0.8562–1.1577. No decay correction applied. $R = 0.035$, $R_w = 0.062$ and G.O.F. = 1.45.

Crystal data for 9b·DMF

$C_{29}H_{33}O_3NFe$, $M = 499.43$. Triclinic, $a = 10.653(1)$, $b = 14.864(2)$, $c = 8.171(2)$ Å, $\alpha = 95.02(1)$, $\beta = 101.75(1)$, $\gamma = 79.45(1)°$, $U = 1243.6(3)$ Å^3, space group $P1$, $Z = 2$, $D_c = 1.334$ g cm^{-3}. Orange, prismatic crystal. Crystal dimensions 0.32 × 0.20 × 0.16 mm, μ(Cu-Kα) = 51.02cm^{-1}. 3321 unique reflections ($2\theta < 113.7°$), 3058 with $I > 2\sigma(I)$, transmission factors: 0.8499–1.3124. No decay correction applied. $R = 0.052$, $R_w = 0.071$ and G.O.F = 1.43.

Crystal data for 9c

$C_{36}H_{28}O_2Cl_2Fe$, $M = 619.37$. Monoclinic, $a = 12.924(1)$, $b = 13.981(2)$, $c = 16.282(2)$ Å, $\beta = 97.30(1)°$, $U = 2918.1(5)$ Å^3, space group $P2_1/n$, $Z = 4$, $D_c = 1.410$ g cm^{-3}. Orange, plate-like crystal. Crystal dimensions 0.34 × 0.25 × 0.16 mm. μ(Cu-Kα) = 60.79 cm^{-1}. 4103 unique reflections ($2\theta < 113.6°$), 3440 with $I > 2\sigma(I)$, transmission factors: 0.8215–1.4452. No decay correction applied. $R = 0.045$, $R_w = 0.069$ and G.O.F = 1.36.

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