Formation and Structures of Dimeric Compounds from an (*E*)-5,5′-Diphenyl-2,2′,3,3′-tetrahydro-3,3′-bipyrrolylidene-2,2′-dione

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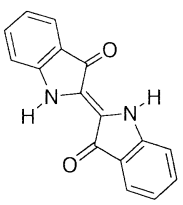
Dimeric fluorescent compounds were formed from an (*E*)-5,5′-diphenyl-2,2′,3,3′-tetrahydro-3,3′-bipyrrolylidene-2,2′-dione by a treatment with acid anhydride and TFA. The structures of these compounds were clarified by X-ray analysis and spectral (UV-vis, ^{1}H and ^{13}C NMR) comparisons.

Among natural pigments, indigo (**1**) is one of the well-known dyes, and *N*,*N*′-diacylindigo has been shown to have properties of a functional dye.[1] A variety of compounds are included in the indigo group, and an (*E*)-5,5′-diphenyl-2,2′,3,3′-tetrahydro-3,3′-bifuranylidene-2,2′-dione **2** is one of the indigoid.[2] We previously reported that an (*E*)-5,5′-diphenyl-2,2′,3,3′-tetrahydro-3,3′-bipyrrolylidene-2,2′-dione **3**, a nitrogen analog of **2**, had a chromophore similar to that of a natural blue pigment, trichotomine (**4**),[3] which bore two indole rings instead of phenyl rings.[4] During a study of the properties of the C^{4}- and $C^{4'}$-acyl derivatives of **3**, we found that dimeric fluorescent compounds **5** and **6** were formed from **3** by a treatment with acetic anhydride/trifluoroacetic acid (TFA) and propionic anhydride/TFA, respectively. This paper deals with the structures of **5** and **6** (Chart 1).

Results and Discussion

Acylation of 3. Compound **3** was prepared from **2** by aminolysis with methylamine, followed by dehydration with acetic anhydride and acetic acid.[4] The C^{4}=C^{5} and $C^{4'}$=$C^{5'}$ double bonds of the enamide systems in **3** were expected to have nucleophilic properties, since the enamide C^{1}=C^{11b} double bond in **7** was acylated to give **8** by a treatment with acetic anhydride and TFA.[5] Thus, the acylation of **3** was examined. Upon a treatment with acetic anhydride and TFA, **3** gave a yellow fluorescent compound **5** as a main product and a monoacetyl derivative **9** as a minor product. A diacylated derivative was obtained using strong conditions. Upon a treatment with trifluoroacetic anhydride (TFAA) and TFA, **3** yielded a diacyl derivative **10**. The formation of **9** and **10** indicated the enamine-type reactivi-



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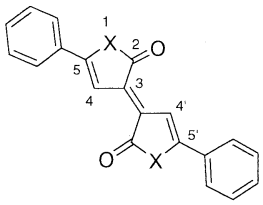
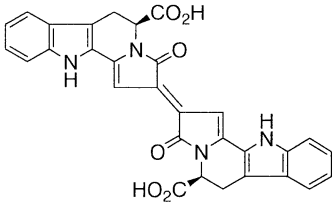


2 X = O
3 X = NMe



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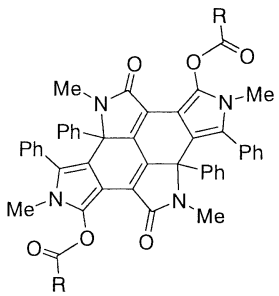
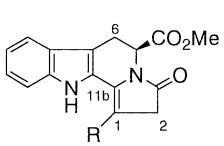
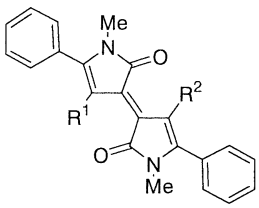


5 R = Me
6 R = Et



7 R = H
8 R = CF_3CO



9 R^1 = CH_3CO R^2 = H
10 R^1 = R^2 = CF_3CO

Chart 1.

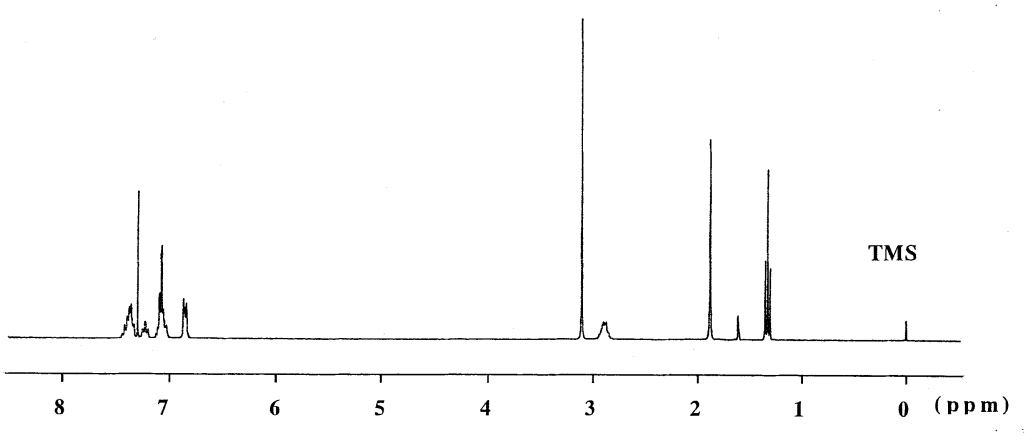


Fig. 1. ^{1}H NMR spectrum of **6** in $CDCl_3$.

ty of the C^4=C^5 and $C^{4'}$=$C^{5'}$ double bonds in **3**. The ^{1}H NMR spectrum of **5** showed three singlet methyl signals at δ = 1.87, 2.51, and 3.10. The ^{13}C NMR spectrum of **5** indicated a characteristic signal at δ = 70.5, suggesting the presence of a quaternary carbon. The mass spectrum showed a peak at *m/z* 767 (M^+ + H), indicating a dimeric structure for **5**. Upon a treatment with propionic anhydride and TFA, **3** similarly afforded a yellow fluorescent compound **6**. As shown in Fig. 1, the ^{1}H NMR spectrum of **6** indicated two singlet *N*-methyl signals at δ = 1.86 and 3.08, and propionyl signals at δ = 1.32 (3H, t, *J* = 7.5 Hz) and 2.87 (2H, m). Therefore, the presence of strongly shielded *N*-methyl groups in **5** (δ = 1.87) and **6** (δ = 1.86) was indicated. The methylene signals at δ = 2.87 suggested steric congestion around the propionyl groups. In the ^{13}C NMR spectra of **5** and **6**, the chemical sifts of the signals of **5** were in agreement with those of the corresponding signals of **6** within 0.1 ppm, except for the acetyl and propionyl signals. Compounds **5** and **9** were not stable, and slowly decomposed during crystallization from $CHCl_3$–MeOH or $CHCl_3$–hexane. Attempts to obtain single crystals of **5** were unsuccessful, but, recrystallization of **6** from $CHCl_3$–MeOH gave single crystals containing $CHCl_3$ as a solvent of crystallization, and were subjected to X-ray analysis. The unexpected structure of **6** was clarified. Compound **6** is a dimer of the acylated intermediate formed from **3**. Two propionyl groups are attached to two oxygen atoms, which arise from the lactam carbonyl oxygen atoms. Two phenyl groups are attached to two quaternary sp^3 carbons, which are assigned to the ^{13}C NMR signal at δ = 70.4. Two kinds of *N*-methyl groups are present, being in line with the ^{1}H NMR signals at δ = 1.86 (3H × 2) and 3.08 (3H × 2).

Comparisons of the spectral data (UV-vis, ^{1}H and ^{13}C NMR) of **5** with those of **6** indicated the described structure for **5**.

Crystal Structure of Compound 6. The crystal structure of **6**·$CHCl_3$ consists of two bipyrrole units and an interstitial chloroform. An ORTEP drawing of **6**·$CHCl_3$ is shown in Fig. 2, and the selected bond distances and bond angles with their estimated standard deviations are listed in Table 1. There is no symmetry element in **6**·$CHCl_3$, while the NMR data indicate the existence of a two-fold axis on **6**, as mentioned above. It may be due to the crystal packing interaction between an interstitial chloroform and **6**, as shown in Fig.3. The phenyl and propionyl groups on the adjacent molecules of **6** project out from each other to create a cage, and two interstitial chloroform molecules are included in the cage. Interestingly, the distance between C(51′) and O(6) is 3.17 Å, and there is a short C–H···O contact between the chloroform and O(6).[6] The structure of the mother skeleton in **6** is nearly symmetrical, and an apparent two-fold axis perpendicular to the mother skeleton passes through the center of the molecule, that is, the center of the C(3)–C(11) bond. The phenyl groups attached to quaternary C(4) and C(12) are located in the same direction, and are perpendicular to the mother skeleton. The bond lengths of C(5)–C(25) and C(13)–C(42) are 1.476(4) and 1.482(4) Å, respectively, which are shorter than those of C(4)–C(18) and

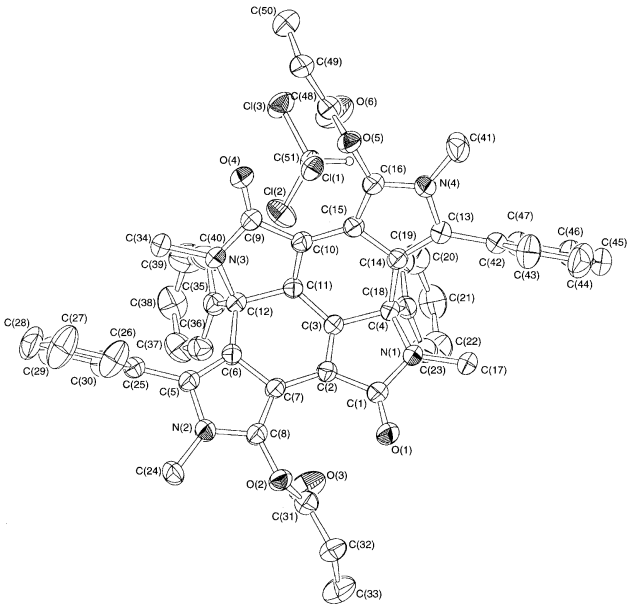


Fig. 2. The crystal structure and atom labeling scheme of **6**·$CHCl_3$. Thermal ellipsoids are at 50% probability level except for $CHCl_3$ (20% probability ellipsoids). Hydrogen atoms are not shown for clarity except for hydrogen atom on $CHCl_3$, H(43).

Table 1. Selected Bond Lengths and Bond Angles for **6**·$CHCl_3$

Bond lengths (Å)			
O(1)–C(1)	1.228(3)	O(2)–C(8)	1.374(3)
O(4)–C(9)	1.222(3)	O(5)–C(16)	1.377(3)
N(1)–C(1)	1.371(4)	N(1)–C(4)	1.476(4)
N(2)–C(5)	1.394(4)	N(2)–C(8)	1.362(4)
N(3)–C(9)	1.369(4)	N(3)–C(12)	1.484(4)
N(4)–C(13)	1.393(4)	N(4)–C(16)	1.356(4)
C(1)–C(2)	1.479(4)	C(2)–C(3)	1.330(4)
C(2)–C(7)	1.452(4)	C(3)–C(4)	1.515(4)
C(3)–C(11)	1.431(4)	C(4)–C(14)	1.525(4)
C(4)–C(18)	1.538(4)	C(5)–C(6)	1.376(4)
C(5)–C(25)	1.476(4)	C(6)–C(7)	1.446(4)
C(6)–C(12)	1.525(4)	C(7)–C(8)	1.359(4)
C(9)–C(10)	1.488(4)	C(10)–C(11)	1.335(4)
C(10)–C(15)	1.438(4)	C(11)–C(12)	1.522(4)
C(12)–C(35)	1.543(4)	C(13)–C(14)	1.374(4)
C(13)–C(42)	1.482(4)	C(14)–C(15)	1.442(4)
C(15)–C(16)	1.358(4)		
Bond angles (°)			
C(1)–N(1)–C(4)	113.1(2)	C(5)–N(2)–C(8)	108.8(2)
C(9)–N(3)–C(12)	113.4(2)	C(13)–N(4)–C(16)	108.6(2)
N(1)–C(1)–C(2)	106.3(2)	C(1)–C(2)–C(3)	108.3(3)
C(2)–C(3)–C(4)	112.5(3)	N(1)–C(4)–C(3)	99.4(2)
N(2)–C(5)–C(6)	107.4(2)	C(5)–C(6)–C(7)	119.3(3)
C(6)–C(7)–C(8)	106.3(3)	N(2)–C(8)–C(7)	110.0(3)
N(3)–C(9)–C(10)	106.2(3)	C(9)–C(10)–C(11)	107.7(3)
C(10)–C(11)–C(12)	113.2(3)	N(3)–C(12)–C(11)	98.8(2)
N(4)–C(13)–C(14)	107.3(3)	C(13)–C(14)–C(15)	107.7(3)
C(14)–C(15)–C(16)	105.9(3)	N(4)–C(16)–C(15)	110.4(3)

C(12)–C(35) [1.538(4) and 1.543(4) Å respectively]. Thus, the phenyl groups on C(5) and C(13) are conjugated with the C(5)–C(6) and C(13)–C(14) double bonds, respectively. Furthermore, the C(17) and C(34) methyl groups are located above the benzene rings on C(13) and C(5), respectively. Accordingly, in the ^{1}H NMR spectrum of **6**, the singlet observed at δ = 1.86 is assigned to the C(17) and C(34) methyl groups.

Reaction Mechanism. A plausible mechanism for the formation of **5** and **6** is shown in scheme 1. The initial step might be the formation of an acylated intermediate (A). In the next step, an intermediate (B) might be formed by a nucleophilic attack of the enamine-type C^4=C^5 double bond in **3** onto C^5 of the intermediate (A). Acylation of the lactam carbonyl group in (B) might yield an intermediate (C). The cyclization shown in (C), and subsequent cyclization in the resulting intermediate (D), followed by dehydrogenation, might give **5** and **6**.

The reaction between (*E*)-5,5′-dimesityl-2,2′,3,3′-tetrahydro-3,3′-bifuranylidene-2,2′-dione, an analog of **2**, and the Horner–Wittig reagent is reported.[7] The formation of dimeric compounds **5** and **6** indicates nucleophilic reactivity of the enamide C^4=C^5 double bond in **3**, and electrophilic reactivity of the intermediate formed by acylation of the lactam carbonyl group in **3**.

Experimental

All melting points are uncorrected. Absorption spectra were measured on a Shimadzu-UV-3100 in $CHCl_3$. Fluorescence spectra were recorded on a Hitachi F-4500 in $CHCl_3$. ^{1}H and ^{13}C NMR spectra were measured on a Bruker AC300 (300 MHz, 75 MHz) in $CDCl_3$, using a $CHCl_3$ signal (δ_H = 7.26 and δ_C = 77.05) as an internal standard. MS spectra were obtained on a JEOL-DX303 by the FAB method. Column chromatography was performed with silica

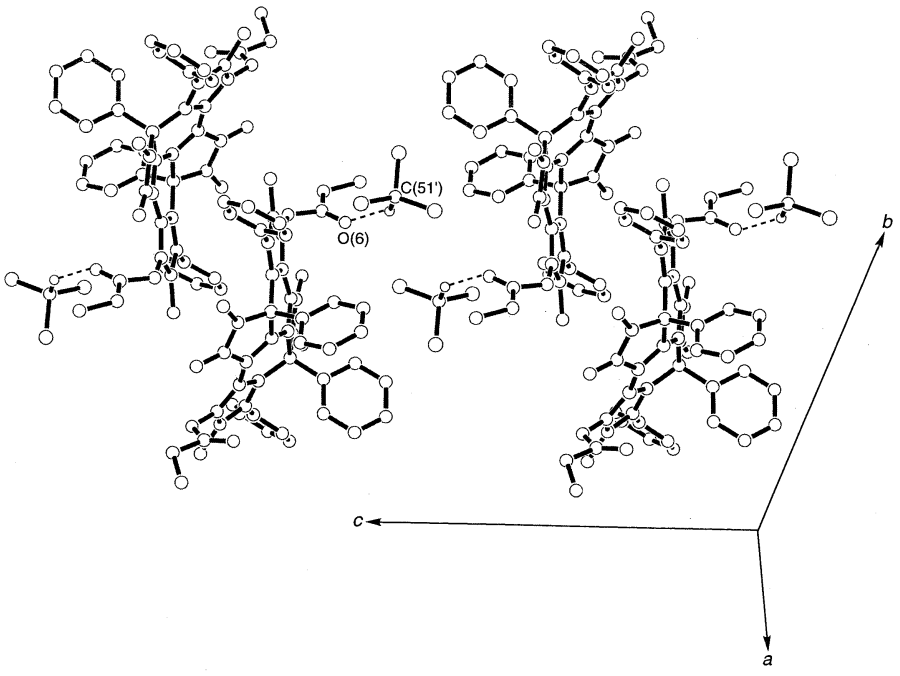
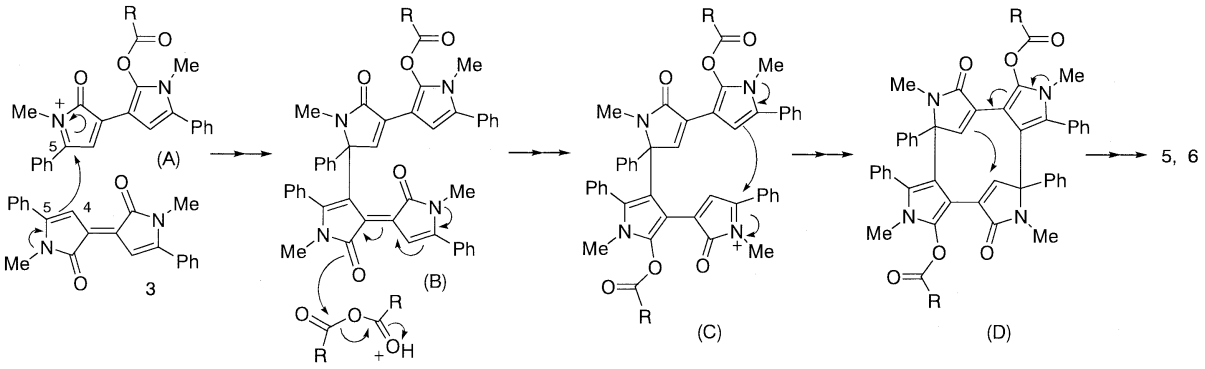


Fig. 3. Crystal packing diagram of **6**·$CHCl_3$. Hydrogen atoms are not shown for clarity except for hydrogen atom on $CHCl_3$. The dashed lines denote the sites of C–H···O interaction.



Scheme 1. A plausible mechanism for the formation of **5** (R = Me) and **6** (R = Et).

Table 2. Crystallographic Data for **6**·$CHCl_3$

Chemical Formula	$C_{51}H_{43}Cl_3O_6N_4$
Formula Weight	914.28
Crystal Size	$0.70 \times 0.30 \times 0.30$ mm^3
Unit-cell Dimensions:	
	a = 12.029(3) Å
	b = 14.063(3) Å
	c = 15.035(3) Å
	α = 109.65(2)°
	β = 102.37(2)°
	γ = 104.08(2)°
Volume of unit cell	2197(1) Å^3
Crystal System	Triclinic
Space Group	$P\bar{1}$ (#2)
Z value	2
Densities: D_{calc}	1.381 g cm^{-3}
F(000)	952.00
Linear Absorption Coefficient	2.65 cm^{-1} (Mo $K\alpha$)
Diffractometer used	Mac science MXC3
Radiation	Mo $K\alpha$ (λ = 0.71073 Å)
$2\theta_{max}$	55.0°
Total Reflections Measured	10824
Unique Reflections	10090
Internal Consistency: Rint	0.014
Function Minimized	$\sum[w(\|F_o\| - \|F_c\|)^2]$
Least Squares Weights	$w = 1.0/\sigma^2(F_o) = [\sigma_c{}^2(F_o)+$
	$p^2/4 \times F_o{}^2]^{-1}(\sigma_c(F_o)$ = e.s.d. based on counting statistics)
p-factor	0.0250
Reflections used ($F > 1.50$ (sig(F))	5963
No. of Variables	577
Residuals: R; R_w	0.063; 0.057
Goodness of Fit Indicator	1.49
Maximum Shift/Error in final cycle	0.00
Maximum Negative Peak in Final Diff. Map	−0.36 e$^-$/Å^3
Maximum Positive Peak in Final Diff. Map	0.32 e$^-$/Å^3

gel 60 (70–230 mesh, Merck) and $CHCl_3$.

Formation of 5 and 9. A mixture of **3** (102 mg, 0.30 mmol), acetic anhydride (2 ml, 21 mmol), and TFA (0.5 ml, 6.5 mmol) was stirred at room temperature for 1 d. The resulting solution was neutralized with aqueous $NaHCO_3$, and extracted with $CHCl_3$. The extracts were dried over Na_2SO_4, and concentrated under reduced pressure. The residue was separated by column chromatography to give **5** (28 mg, 25%) and **9** (as an oil, 13 mg, 11%). **5**: Mp > 300 °C ($CHCl_3$–MeOH); UV-vis 429 (ε 11100) and 453 nm (sh, 9100); Fluorescence λ_{max} = 508 nm (excitation at 430 nm); ^{1}H NMR δ 1.87 (3H × 2, s), 2.51 (3H × 2, s), 3.10 (3H × 2, s), 6.82 (2H × 2, m), and 6.98–7.43 (8H × 2, m); ^{13}C NMR δ 20.9, 29.3, 29.8, 70.5, 102.2, 119.5, 123.0, 126.5, 127.3, 128.0, 128.3, 128.6, 128.8, 129.1, 130.8, 132.5, 133.4, 139.4, 148.5, 169.8, and 170.2; MS *m*/*z* 767 (M^+ + H). Found: C, 71.18; H, 4.98; N, 6.84%. Calcd for $C_{48}H_{38}N_4O_6$·0.4 $CHCl_3$: C, 71.36; H, 4.75; N, 6.88%. **9**: UV-vis

299 (ε 16800) and 562 nm (13000); ^{1}H NMR δ 2.16 (3H, s), 3.02 (3H, s), 3.18 (3H, s), 7.08 (1H, s), 7.40–7.60 (10H, m); ^{13}C NMR δ 27.8, 28.6, 32.1, 103.4, 118.5, 124.4, 127.9, 128.7, 128.9, 129.1, 130.4, 130.5, 131.7, 150.6, 155.0, 169.2, 170.0, and 197.7. Found: *m/z* 385.1560. Calcd for $C_{24}H_{21}N_2O_3$: M + H, 385.1552.

Formation of 10. A mixture of **3** (102 mg, 0.30 mmol), TFAA (2 ml, 14 mmol), and TFA (0.5 ml, 6.5 mmol) was stirred at room temperature for 1 d. The resulting solution was worked up, as described above, to give **10** (36 mg, 23%): Mp > 300 °C ($CHCl_3$–hexane); UV-vis 314 (ε 12900) and 554 nm (12700); ^{1}H NMR δ 3.04 (3H × 2, s) and 7.40–7.60 (5H × 2, m); ^{13}C NMR δ 28.6, 109.1, 114.6, 118.4, 126.8, 128.8, 129.0, 131.4, 160.2, 168.4, 177.6. Found: *m/z* 535.1120. Calcd for $C_{26}H_{17}F_6N_2O_4$: M + H, 535.1093.

Formation of 6. A mixture of **3** (102 mg, 0.30 mmol), propionic anhydride (2 ml, 16 mmol), and TFA (0.5 ml, 6.5 mmol) was stirred at room temperature for 1 d. The resulting solution was worked up, as described above, to give **6** (20 mg, 20%): Mp > 300 °C ($CHCl_3$–MeOH); UV-vis 429 (ε 10100) and 453 nm (sh, 8200); Fluorescence λ_{max} = 496 nm (excitation at 425 nm); ^{1}H NMR δ 1.32 (3H × 2, t, J = 7.5 Hz), 1.86 (3H × 2, s), 2.87 (2H × 2, m), 3.08 (3H × 2, s), 6.81 (2H × 2, m), and 6.97–7.42 (8H × 2, m); ^{13}C NMR δ 8.9, 27.4, 29.3, 29.8, 70.4, 102.2, 119.5, 123.0, 126.5, 127.3, 127.9, 128.3, 128.6, 128.7, 129.1, 130.8, 132.6, 133.4, 139.4, 148.4, 170.2, and 173.3. Found: *m/z* 795.3309. Calcd for $C_{50}H_{43}N_4O_6$: M + H, 795.3183. Found: C, 71.20; H, 5.12; N, 6.56%. Calcd for $C_{50}H_{42}N_4O_6$·0.5 $CHCl_3$: C, 70.98; H, 5.01; N, 6.56%.

Crystallographic Data Collection and Refinement of the Structure. A suitable crystal was chosen and mounted on a glass fiber with epoxy resin. Data collection for the compound **6**·$CHCl_3$ was carried on a MAC Science MXC3 with graphite-monochromated Mo-$K\alpha$ radiation. Crystallographic data are given in Table 2. The structure was solved by direct methods (Rigaku TEXSAN crystallographic software package of Molecular Structure Corporation). All non-H atoms were refined anisotropically. All of the hydrogen atoms were observed and refined with a fixed value of the isotropic displacement parameters.

The complete F_o–F_c data together with relevant data including bond distances and angles have been deposited as Document No. 74024 at the Office of the Editor of Bull. Chem. Soc. Jpn. Crystallographic data have been also deposited at the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK and copies can be obtained on request, free of charge, by quoting the publication citation and the deposition number 150417.

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