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Title: Preparations, Crystal Structures and DFT calculation of diacetylene derivatives carrying nicotinic esters

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1. Introduction

Polydiacetylenes (PDAs), which are classified into conjugated polymers [1,2], have attracted not only from their physical properties originating from one-dimensional π -conjugated systems such as non-linear optics [3] or conductivity [4-6], but also from application to chemosensors [7]. PDAs are prepared by solid-state-polymerization of diacetylene monomers, where relative orientation of monomers is quite important for the polymerization [8] because molecular motions are restricted in their crystals. Many PDAs have a $-(CH_2)_n-$ side chain adjacent to the backbone in order to reduce lattice strain caused by the solid-state polymerization. However, *gauche* or pseudo *gauche* conformation of the side chain frequently prevents suitable molecular orientation for the polymerization. Examples of the polymerization in *gauche* conformer are limited to some diacetylenes [9].

Pyridines have a large variety of chemical modification such as oxidation, protonation or *N*-alkylation [10]. Pyridines can also work as ligands for metal complexes or hydrogen-bond acceptors in supramolecular complexes [11]. PDAs carrying pyridyl pendant groups promise to give novel functional materials. Few PDAs

carrying a pyridyl unit, however, have been reported as a single component judged by their crystal packing structures. While Lauher *et al.* have **proposed** several crystal designs for arranging pyridine-containing diacetylene derivatives by utilizing template molecules [12,13].

We report herein preparation and crystal structures of novel three pyridine-containing diacetylenes and discuss their molecular structures based on intermolecular interactions and DFT calculation.

2. Experimental

2.1. General Procedure

All chemicals were purchased from Kanto Chemical Co. Ltd. or Tokyo Kasei Kogyo Co. Ltd. and were used without further purification. Compound **1** was prepared according to the literature [12]. ^1H and ^{13}C NMR spectra were recorded on a JEOL JNM-ECA-400 spectrometer in a deuterated solvent (chloroform-*d*) with tetramethylsilane as an internal standard. All ^{13}C NMR spectra were obtained with

complete proton decoupling. IR spectra were recorded on a JASCO FT/IR-420 spectrometer by using a KBr pellet. Elemental analysis was performed on a J-SCEINCE LAB MICRO CORDER JM10.

2.2. Crystallographical analysis

X-ray crystallographic data of **1-3** were obtained by a RIGAKU Saturn 724+ CCD device using multi-layered mirror monochromatic Mo $K\alpha$ radiation at 93 K. The structures were solved by a direct method (SHELXD) [14] and were refined by full-matrix least-squares method (SHELXL97) [15]. The positions of non-H atoms were obtained from difference Fourier maps and were refined anisotropically. The C-bound H atoms were obtained by calculation and were refined as riding on their parent C atoms. $U_{\text{iso}}(\text{H})$ values of the H atoms were set at $1.2U_{\text{eq}}$ (parent C atoms). The N-bound and O-bound H atoms were obtained from difference Fourier maps and were refined isotropically.

2.3. DFT calculations

DFT calculations were performed on the GAMESS software [16,17] with B3LYP 6-31G (*d,p*) level. The geometrical optimization was carried out in C1 symmetry, where the initial structures for calculations were set at those obtained by crystallographical analyses or by calculations of RHF 6-31G(*d*) level.

2.4. Materials

Preparation of 6-hydroxyhexa-2,4-diyne-1-yl nicotinate (2)

After a suspension of copper chloride (I) (1.34 g, 13.5 mmol) in acetone (55 mL) was degassed by argon bubbling for 30 min, *N,N,N',N'*-tetramethylethylenediamine (TMEDA) (0.60 mL, 4.0 mmol) was added to the suspension, and it was stirred for 30 min. The suspension containing Cu-TMEDA catalysis was transferred into a solution of prop-2-yn-1-yl nicotinate (2.00 g, 12.4 mmol) and 2-propyn-1-ol (4.0 mL, 67.6 mmol) in acetone (65 mL). The solution was stirred for 45 h under an oxygen atmosphere. The solvent was evaporated, and the residue was extracted with chloroform (150 mL). The solution was washed four times with 5% ammonium hydroxide (50 mL) and three times

with water, and dried over anhydrous sodium sulfate. The solvent was evaporated after filtration, and the residue was purified by column chromatography on a silica gel with a mixed solution of hexane and ethyl acetate ($v/v = 1:3$) as eluent to give 1.12 g (yield 42 %) of **2** as a yellowish white powder. ^1H NMR (400 MHz, CDCl_3): 2.68 (s, 1H, OH), 4.36 (s, 2H, CH_2OH), 5.04 (s, 2H, CH_2OCO), 7.44 (ddd, 1H, $^3J=8.0$, 4.9 Hz, and $^5J=0.8$ Hz, N/C5H4-H5), 8.34 (td, 1H, $^3J=8.0$ Hz and $^4J=2.2$ Hz, N/C5H4-H4), 8.80 (dd, 1H, $^3J=4.9$ Hz and $^4J=1.7$ Hz, N/C5H4-H6), 9.25 (dd, 1H, $^4J=2.2$ Hz and $^5J=0.8$ Hz, N/C5H4-H2). ^{13}C NMR (100 MHz, CDCl_3): 51.2; 53.3; 69.3; 71.2; 72.5; 78.6; 123.5; 125.4; 137.5; 150.9; 153.7; 164.4. IR (KBr / cm^{-1}): 3176 (ν_{OH}), 1729 ($\nu_{\text{C=O}}$). Anal. Calc. for $\text{C}_{12}\text{H}_9\text{NO}_3$: C, 66.97; H, 4.22; N, 6.51 %. Found; C, 67.01; H, 4.22; N, 6.40 %.

Preparation of 6-((phenylcarbamoyl)oxy)hexa-2,4-diyne-1-yl nicotinate (3)

A solution of **2** (0.51 g, 2.4 mmol) and phenylisocyanate (0.38 mL, 3.5 mmol) in THF (18 mL) was stirred for 36 hours under an argon atmosphere. The solution was concentrated and the residual solid was purified by column chromatography on a silica gel with a mixed solution of hexane and ethyl acetate ($v/v = 1:1$) as an eluent to give

0.37 g (46 %) of **3** as pale pink powder. ^1H NMR (400 MHz, CDCl_3): 4.85 (s, 2H, CH_2OH), 5.03 (s, 2H, CH_2OCO), 6.87 (s, 1H, NH), 7.09 (t, 1H, $^3J=7.2$ Hz, $\text{C}_6\text{H}_5\text{-H}_p$), 7.31 (dd, 2H, $^3J=7.24$, 7.8 Hz, $\text{C}_6\text{H}_5\text{-H}_m$), 7.38 (d, 2H, $^3J=8.0$ Hz, $\text{C}_6\text{H}_5\text{-H}_o$), 7.42 (dd, 1H, $^3J=8.0$, 4.9 Hz, N/C $5\text{H}_4\text{-H}_5$), 8.32 (dt, 1H, $^3J=8.0$, and $^4J=2.3$ Hz, N/C $5\text{H}_4\text{-H}_4$), 8.81 (d, 1H, $^3J=4.9$ Hz, N/C $5\text{H}_4\text{-H}_6$), 9.25 (s, 1H, N/C $5\text{H}_4\text{-H}_2$). ^{13}C NMR (100 MHz, CDCl_3): 53.0; 53.1; 70.4; 70.9; 73.1; 74.2; 118.8; 123.4; 123.9; 125.2; 129.1; 137.2; 137.3; 151.1; 152.2; 153.9; 164.4. IR (KBr / cm^{-1}): 3251 (ν_{NH}), 3042 (ν_{CH}), 1727 ($\nu_{\text{C=O}}$).
Anal. Calc. for $\text{C}_{19}\text{H}_{14}\text{N}_2\text{O}_4$: C, 68.26; H, 4.22; N, 8.38 %. Found: C, 68.02; H, 4.22; N, 8.31 %.

3. Results and discussion

3-1 Preparation of compound 1-3

Preparation of compound **1-3** was shown in Scheme 1. Hay coupling of prop-2-yn-1-yl nicotinate gave symmetric diacetylene **1** with 69 % yield [12]. Compound **2** was also obtained by the similar coupling of prop-2-yn-1-yl nicotinate

with excess of 2-propyn-1-ol in 42 % yield. Condensation of **2** with phenylisocyanate afforded **3** in 46 % yield.

3.2. Crystal Structure of **1-3**.

The single crystals of **1-3** with sufficient quality were obtained by slow evaporation from a chloroform solution for **1**, a hexane-chloroform solution for **2** and a hexane-acetone solution for **3**. Crystal data and geometric parameters of **1-3** are summarized at Table 1 and Table S1, respectively.

Figure 1(a) shows the crystal structure of **1** in which a half of the molecule is crystallographically independent. The molecules have a chair form owing to bend at a CH₂ part, whose angle is 110.57(16)°. The dihedral angle between the N1/C1-C5 pyridine rings is 178.03(6)°. The dihedral angle between the pyridine ring with the C6/C7/O1/O2 ester part is 5.38(6)°, showing effective conjugation. The torsion angle of C6-O2-C7-C8 is -89.52(17)°, indicating pseudo *gauche* conformation.

The molecular packing structure was shown in Figure 1(b). The molecules stack along the *a* axis, where the pyridine rings within the column make alternative stacks

with the ring of the neighboring column forming a layered structure within the *ac* plane. Intermolecular contacts within the layer are recognized at C1 and C4 whose distances are 3.386(3) Å for C1...C1ⁱⁱ, 3.288(3) Å for C4...C6ⁱⁱⁱ. Weak C-H... π and C-H...O bonds are also found between the layers. The diacetylenic units have an inclination angle of 32.31(4)° to the *a* axis and C8...C8^v distance is 4.088(3) Å. These stacking parameters do not satisfy the Baughman's condition [8].

Cocrystal of **1** with 2,2'-(oxalylbis(azanediyl))diacetic acid has already been reported by Fowler and Lauher [12]. In the cocrystal, **1** has *anti* conformation in the ester group and make an ideal orientation for solid-state-polymerization of diacetylenes by means of complexation with the template molecule. The *anti* conformation is rather stable than gauche one (*vide infra*) and seems to be favorable for one-dimensional stacks of nicotinate ester derivatives.

Figure 2(a) shows the crystal structure of **2**. The structure of nicotinate ester part is planar. The molecules have a roof form owing to bend at a CH₂ part, whose angles are 112.82(15)°. The torsion angle of C6-O2-C7-C8 is -71.11(17)°, showing pseudo *gauche* conformation. Figure 2(b) shows the molecular stacking structure along the *a* axis. The

diacetylenic units have an inclination angle of $69.53(5)^\circ$ to the a axis and stacking intervals of $4.066(3)$ Å, resulting that the $C11\cdots C8^i$ distance is $4.476(3)$ Å. These stacking parameters do not satisfy the Baughman's condition. These one-dimensional stacks were connected by intermolecular $O-H\cdots N$ hydrogen bonds, which are expressed by C(13) according to the graph set notation. The $O\cdots N$ distance of $2.808(2)$ Å indicates a strong interaction.

Figure 3(a) shows the crystal structure of **3**. The nicotinate ester and phenyl urethane units have a planar structure, and the molecules twist largely at two CH_2 parts whose angles are $107.17(16)^\circ$ and $108.16(16)^\circ$, respectively. The torsion angle of $C6-O2-C7-C8$ is $170.71(12)^\circ$, showing pseudo *anti* conformation.

Two $N-H\cdots N_{py}$ hydrogen bonds, whose $N\cdots N$ distance is $3.027(3)$ Å, make $R_2^2(30)$ dimeric forms. The dimers stack along the b axis forming a columnar structure with stacking intervals of $4.880(3)$ Å. The inclination angle of the diacetylenic unit with the b axis is $48.69(4)^\circ$. These stacking parameters satisfy the Boughman's condition and the compound shows solid-state-polymerization reactivity.

3-3 Comparison of the crystal structures

The all compounds make a columnar structure. In compound **1**, pyridyl groups form an alternate stack with a neighboring column. In compound **2**, the molecules make a regular 1D-stacking structure, but polymerization could not be detected because of large inclination angle between the diacetylene moiety and the stacking axis, which is thought to be originated in π - π stacking interaction. In compound **3**, the molecules form a hydrogen-bonded dimer and the dimers make a 1-D stack. The local orientation of the monomers is appropriate for the solid-state-polymerization. In all compounds, pyridine-pyridine interactions are found to have a crucial role for the molecular stacking. The largest difference among their molecular structures is conformation at nicotinate ester parts. Namely, **1** and **2** have *gauche* conformation, while **3** does *anti* conformation.

DFT calculations of **1-3** were performed with B3LYP 6-31G(*d*) level of theory and the optimized structures were summarized in Figure S7-S9. *Anti* conformation is found to be stable in all compounds and *gauche* conformation is less stable. Namely, the optimization could reproduce only the molecular structure of **3**. However, the energy differences between *anti* and *gauche* conformers are essentially very small, and the

conformation in the crystals is considered to be affected mainly by intermolecular interactions.

3-4 Crystal structures of other diacetylenes carrying a nicotinate or isonicotinate group

According CSD, there are four examples for crystal structures of diacetylene compounds which have a nicotinate or isonicotinate group [9,12,13,18,19]. No crystals showed polymerization reactivity which had *gauche* conformation at their ester parts including the present crystals. The *gauche* conformer seems to afford unfavorable stacks for solid-state-polymerization of diacetylenes.

4. Conclusion

We have successfully prepared and crystallographically analyzed novel three diacetylene derivatives **1-3**, which carry a pyridine ring as a pendant group. In compound **1**, the molecular stacks form a layered structure within the *ac* plane. In **2**, the

molecules make a columnar stack along the *a* axis. In **3**, the molecules have a dimeric form and the dimers make a 1D-stack along the *b* axis.

The all compounds form a columnar stack, but the conformation at nicotinate ester part is found to make significant difference for molecular arrangement. The *gauche* conformation at nicotinate ester part (**1** and **2**) makes an intermolecular π - π interaction between pyridine groups. This interaction between stacks prevents to make independent molecular stacks in **1** and makes a larger inclination angles than ideal one for solid-state polymerization of diacetylenes in **2**. The *anti* conformation in **3** caused by N-H $\cdots$ N hydrogen-bonding makes it possible to stack one-dimensionally with moderate inclination angle, which is suitable for the polymerization.

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(a)

(b)

Figure 1.(a)Molecular structure of **1** with atom-numbering scheme [symmetry code: (i) $-x, y, 3/2-z$]. Displacement ellipsoids are drawn at the 50% probability level and H atoms are shown as small spheres. (b) Molecular packing structure of **1** [symmetry codes:(ii) $1-x, y, 1/2-z$ (iii) $-x, y, 1/2-z$ (iv) $1+x, y, z$ (v) $1-x, y, 3/2-z$].

(a)

(b)

Figure 2.(a) Asymmetric unit of **2** with atom-numbering scheme. Displacement ellipsoids are drawn at the 50% probability level and H atoms are shown as small spheres. (b) Molecular packing structure of **2** [Symmetry codes:(i) $1+x,y,z$ (ii) $-1/2+x,3/2-y,1/2+z$].

(a)

(b)

Figure 3.(a) Asymmetric unit of **3** with atom-numbering scheme. Displacement ellipsoids are drawn at the 50% probability level and H atoms are shown as small spheres. (b) Molecular packing structure of **3** [Symmetry codes: (i) $x, 1+y, z$ (ii) $1-x, 2-y, -z$].

Scheme 1. Preparation of **1**, **2** and **3**.

Table 1. Crystal data and refinement details for **1**, **2** and **3**.

Compounds	1	2	3
Empirical formula	C ₁₈ H ₁₂ N ₂ O ₄	C ₁₂ H ₉ NO ₃	C ₁₉ H ₁₄ N ₂ O ₄
Formula weight	320.30	215.21	334.33
Crystal system	<i>Monoclinic</i>	<i>Monoclinic</i>	<i>Monoclinic</i>
Crystal size (mm)	0.10 × 0.08 × 0.01	0.15 × 0.12 × 0.01	0.12 × 0.08 × 0.01
Crystal color	Colorless	Colorless	Colorless
Space group	<i>C2/c</i>	<i>P2₁/n</i>	<i>P2₁/c</i>
<i>a</i> (Å)	6.751(3)	4.0658(11)	17.263(7)
<i>b</i> (Å)	18.919(7)	28.023(7)	4.8799(17)
<i>c</i> (Å)	11.543(4)	8.993(3)	20.084(9)
α (°)	90	90	90
β (°)	94.130(5)	90.773(6)	110.268(6)
γ (°)	90	90	90
<i>V</i> (Å ³)	1470.5(10)	1024.5(5)	1587.1(11)
<i>Z</i>	4	4	4
<i>D_x</i> (Mg/m ³)	1.447	1.395	1.399
μ (mm ⁻¹)	0.104	0.102	0.100
Theta range for data collection (°)	2.2 – 31.3	2.3 – 31.2	1.9 – 31.1
Limiting indices	-8 ≤ <i>h</i> ≤ 7, -22 ≤ <i>k</i> ≤ 21, -13 ≤ <i>l</i> ≤ 13	-4 ≤ <i>h</i> ≤ 4, -33 ≤ <i>k</i> ≤ 32, -10 ≤ <i>l</i> ≤ 10	-22 ≤ <i>h</i> ≤ 21, -5 ≤ <i>k</i> ≤ 6, -24 ≤ <i>l</i> ≤ 26
Reflections collected/unique	4952/1291 (<i>R_{int}</i> = 0.056)	6412/1773 (<i>R_{int}</i> = 0.024)	12235/3631 (<i>R_{int}</i> = 0.038)
Reflections with <i>I</i> > 2σ(<i>I</i>)	981	1455	2636
Refined parameters/restrains	109/0	149/0	230/0
Goodness of Fit on <i>F</i> ²	1.05	1.10	1.07
<i>R</i> ₁ , <i>wR</i> ₂	0.043, 0.105	0.041, 0.109	0.051, 0.130
Data completeness	0.998	0.986	0.993
Data/restrains/parameters	1291/0/109	1772/0/149	3631/0/230
Max. and min. transmission	0.999 and 0.995	0.999 and 0.989	0.999 and 0.992
Largest diff. peak and hole (eÅ ⁻³)	0.20 and -0.20	0.24 and -0.18	0.24 and -0.25