# Journal of Molecular Structure 982 (2010) 16-21

Contents lists available at ScienceDirect

# Journal of Molecular Structure

journal homepage: www.elsevier.com/locate/molstruc

# Control of relationship between conformational and color polymorphs of achiral 2-methyl-3-arylthio-1,4-naphthalenediones

Takafumi Kinuta <sup>a</sup>, Tomohiro Sato <sup>a</sup>, Takunori Harada <sup>b</sup>, Nobuo Tajima <sup>c</sup>, Reiko Kuroda <sup>b,d</sup>, Yoshio Matsubara <sup>a,\*</sup>, Yoshitane Imai <sup>a,\*\*</sup>

<sup>a</sup> Department of Applied Chemistry, Faculty of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, Osaka 577-8502, Japan

<sup>b</sup> JST ERATO-SORST Kuroda Chiromorphology Team, 4-7-6, Komaba, Meguro-ku, Tokyo 153-0041, Japan

<sup>c</sup>Graduate School of Pure and Applied Sciences, Tsukuba University, 1-1-1 Tenodai, Tsukuba, Ibaraki 305-8571, Japan

<sup>d</sup> Department of Life Sciences, Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

# ARTICLE INFO

Article history: Received 19 May 2010 Received in revised form 22 July 2010 Accepted 22 July 2010 Available online 29 July 2010

Keywords: Chiral Crystal-engineering Naphthoquinone Polymorphism

# 1. Introduction

In the field of solid-state chemistry, polymorphism has attracted much attention because the polymorphs of a compound show unique physical and chemical properties in the solid-state [1]. Recently, we have reported that the achiral compound 2methyl-3-(2-naphthalenylthio)-1,4-naphthalenedione (1) shows conformational and color polymorphism (Fig. 1) [2]. One of the polymorphs (IA) is a deep orange and achiral crystal, and the other (IB) is a reddish purple and chiral crystal. Interestingly, the relationship between these polymorphs can be controlled by changing the crystallization conditions.

In general, it is difficult to predict whether a compound can show polymorphism or not. It is more difficult to control the relationship between conformational and color polymorphs of compounds of the same series. In other words, it is more difficult to produce 2-methyl-3-arylthio-1,4-naphthalenedione with two polymorphs (chiral deep orange crystal and achiral reddish purple crystal) as compared to **1**.

In this paper, we attempted to control the relationship between the conformational and color polymorphs of achiral

ABSTRACT

The achiral compound 2-methyl-3-(4-bromophenylthio)-1,4-naphthalenedione shows conformational and color polymorphism. The relationship between the conformational and color polymorphs (chirality and color) of 2-methyl-3-arylthio-1,4-naphthalenediones can change according to the type of arylthio group.

© 2010 Elsevier B.V. All rights reserved.

2-methyl-3-arylthio-1,4-naphthalenedione by using 2-methyl-3-(4-chlorophenylthio)-1,4-naphthalenedione (**2**) and 2-methyl-3-(4-bromophenylthio)-1,4-naphthalenedione (**3**).

# 2. Experimental

#### 2.1. General methods

Crystallization solvents were purchased from Wako Pure Chemical Industry. These solvents were used directly as obtained commercially. Diffuse reflectance spectra (DRS) of crystals were measured with a *HITACHI U-4000 Spectrometer*. The circular dichroism (CD) and absorption spectra were measured using a *Jasco J-800KCM spectrophotometer*. X-ray powder diffraction (XRPD) patterns of crystals were collected on a *Rigaku RINT2500*. <sup>1</sup>H NMR spectra were recorded with a Varian Mercury M300 spectrometer in chloroform-*d* using tetramethylsilane as an internal standard (300 MHz). <sup>13</sup>C NMR spectra were recorded with a Varian Mercury M300 spectrometer in chloroform-*d* using tetramethylsilane as an internal standard (75 MHz).

2.2. Synthesis of 2-methyl-3-(4-bromophenylthio)-1,4-naphthalenedione (**3**)

Compound **3** was synthesized following the literature method for related compounds with some modification [2].





<sup>\*</sup> Corresponding author. Tel.: +81 06 6730 5880x5241; fax: +81 06 6727 2024.

<sup>\*\*</sup> Corresponding author. Tel.: +81 06 6730 5880x5241; fax: +81 06 6727 2024.

*E-mail addresses:* y-matsu@apch.kindai.ac.jp (Y. Matsubara), y-imai@apch.kindai.ac.jp (Y. Imai).

<sup>0022-2860/\$ -</sup> see front matter @ 2010 Elsevier B.V. All rights reserved. doi:10.1016/j.molstruc.2010.07.032



Fig. 1. Photographs of crystals IA and IB. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

2-Methyl-1,4-naphthoquinone oxide (175 mg, 0.93 mmol) and 4bromobenzenethiol (175 mg, 0.93 mmol) were dissolved in *iso*propanol (30 mL). After that, 15% potassium hydroxide (0.05 mL) solution was added to the *iso*-propanol solution. The reaction mixture was stirred at room temperature for 3 h. The mixture was evaporated under vacuum. A diethyl ether (100 mL) was added. The combined organic layers were washed with brine, dried over Mg<sub>2</sub>SO<sub>4</sub>, and evaporated under vacuum to give the crude sulfide

#### Table 1

Crystal data and structure refinement details.

	II	IIIA	IIIB
Formula	C <sub>17</sub> H <sub>11</sub> ClO <sub>2</sub> S	C <sub>17</sub> H <sub>11</sub> BrO <sub>2</sub> S	C <sub>17</sub> H <sub>11</sub> BrO <sub>2</sub> S
Formula	314.77	359.23	359.23
weight			
Temperature	115(2) K	115(2) K	115(2) K
Radiation	Mo(Kα) 0.71073 Å	Mo(Kα) 0.71073 Å	Mo(Kα) 0.71073 Å
Crystal system	Monoclinic	Orthorhombic	Triclinic
Space group	$P2_1/n$	$P2_12_12_1$	P-1
Unit cell dimensions	a = 7.2691(13) Å	a = 5.8375(6) Å	a = 7.6398(6) Å
	b = 24.185(4) Å	b = 13.3827(14) Å	b = 11.3688(8) Å
	c = 7.8234(14) Å	<i>c</i> = 17.8321(18) Å	<i>c</i> = 17.5044(13) Å
	$\alpha = 90.00^{\circ}$	$\alpha = 90.00^{\circ}$	$\alpha = 74.7520(10)^{\circ}$
	$\beta = 91.438(3)^{\circ}$	$\beta = 90.00^{\circ}$	$\beta = 83.2300(10)^{\circ}$
	$\gamma = 90.00^{\circ}$	$\gamma = 90.00^{\circ}$	$\gamma = 82.8380(10)^{\circ}$
Volume (A <sup>3</sup> )	1374.9(4)	1393.1(2)	1449.62(19)
Z, density (g/cm <sup>3</sup> )	4, 1.521	4, 1.713	4, 1.646
$\mu$ (mm $^{-1}$ )	0.430	3.101	2.980
F(000)	648	720	720
Crystal size (mm)	$0.45 \times 0.35 \times 0.10$	$0.40 \times 0.30 \times 0.25$	$0.40 \times 0.35 \times 0.10$
Theta range	1.68-27.86	1.90-27.89	1.87-27.93
Reflection collected/ unique	8220/3127	8476/3176	9009/6318
Data/ parameters	3127/191	3176/191	6318/381
$S$ (on $F^2$ )	1.047	0.925	1.037
$R [I > 2.0\sigma(I)]/$	0.0463/0.0565	0.0258/0.0289	0.0376/0.0440
R [all data]			
wR [I > 2.0	0.1149/0.1216	0.0501/0.0507	0.0972/0.1014
$\sigma(I)]/wR$			
[all data]			
CCDC	763,247	763,248	763,249

compound. Compound **3** was purified by crystallization from diethyl ether in 51% yield. <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  = 2.39 (s, 3H), 7.24 (dd, *J* = 6.6 Hz, *J* = 1.8 Hz, 2H), 7.41 (dd, *J* = 6.6 Hz, *J* = 1.8 Hz, 2H) 7.69–774 (m, 2H), 8.92 (dd, *J* = 6.8 Hz, *J* = 2.2 Hz, 1H), 8.12 (dd, *J* = 6.8 Hz, *J* = 2.2 Hz, 1H). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>):  $\delta$  = 16.3, 31.2, 121.7, 127.0, 127.3, 132.3, 132.5, 132.7, 133.5, 134.0, 134.1, 145.0 149.8, 180.5, 183.2. HR-MS (EI): *m*/*z* [M]<sup>+</sup> calcd for C<sub>17</sub>H<sub>11</sub>BrO<sub>2</sub>S: 357.9663; found: 357.9682.

#### 2.3. X-ray crystallographic study of crystal

X-ray diffraction data for single crystals were collected using a *BRUKER APEX* instrument. The crystal structures were solved by direct methods [3] and refined by full-matrix least-squares using *SHELXL97* [3]. The diagrams were prepared using *PLATON* [4]. Absorption corrections were performed using *SADABS* [5]. Nonhydrogen atoms were refined with anisotropic displacement parameters, and hydrogen atoms were included in the models in their calculated positions in the riding model approximation. Crystallographic data and details of measurements are summarized in Table 1. The CSD reference number of crystals **II**, **IIIA**, and **IIIB** is 763,247, 763,248, and 763,249, respectively. Crystallographic data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB21EZ, UK; fax:+ 44 1223 336 033; deposit@ccdc.cam.ac.uk).

# 3. Results and discussion

Compounds **2** [6] and **3** were prepared in the same manner as **1**. Reaction of 2,3-epoxy-2-methyl-1,4-naphthoquinone with 4-chlorobenzenethiol (or 4-bromobenzenethiol) and 15% potassium hydroxide solution produced **2** or **3** in 71% and 51% yields, respectively (Scheme 1).

In order to investigate the polymorphism of these compounds, **2** and **3** were crystallized from [diethyl ether and dichloromethane  $(CH_2CI_2)$ ]. For **2**, the same orange color crystals (**II**) were obtained from the two solutions. On the other hand, it was found that **3** had two different colored crystals and the relative proportion of these two crystals depended on the type of the solvent used for slow evaporation. When the diethyl ether solution was used as a solvent, deep orange crystals (**IIIA**) were obtained, but when  $CH_2CI_2$  was used as a solvent, reddish purple crystals (**IIIB**) were



Scheme 1.

obtained (Fig. 2). These two crystals did not contain any other molecules such as those of the crystallization solvent.

The colors of these conformational polymorphs were different, as shown in Fig. 2. Solid-state diffuse reflectance spectra (DRS) of **IIIA** and **IIIB** were measured (Fig. 3).

As expected, the solid-state DRS of **IIIA** and **IIIB** were markedly different; the absorption edges were located at *ca*. 520 and 570 nm, respectively.

To investigate the chirality of these polymorphs, solid-state circular dichroism (CD) spectra of these crystals were measured by using a KBr pellet. Only IIIA showed CD. The solid-state CD and absorption spectra of IIIA, as shown in Fig. 4, indicate that IIIA has chirality.

Peaks originating from the naphthalenedione ring were observed in the CD spectrum at 438 and 504 nm. The circular anisotropy ( $g_{CD} = \Delta OD/OD$ ) factor of the Cotton effect ( $\lambda^{CD} = 504$  nm) was approximately  $8.3 \times 10^{-4}$ . These results suggest that the achiral



**Fig. 2.** Photographs of crystals **IIIA** and **IIIB**. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 3.** Diffuse reflectance spectra (DRS) of crystals **IIIA** (red line) and **IIIB** (black line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 4. Solid-state CD and absorption spectra of crystal IIIA (KBr pellet).

compound **3** has conformational and color polymorphs, each of which exhibits different optical properties.

In order to study the structures of these polymorphs, X-ray crystallographic analyses were performed. IIIA obtained from diethyl ether solution was analyzed first. Its structure is shown in Fig. 5. It is composed of only 3 without the crystallization solvent. As expected, this crystal belongs to the chiral space group P2<sub>1</sub>2<sub>1</sub>2<sub>1</sub>. The torsion angle is -65.9° [C(3)-C(2)-S(12)-C(13)], shifted from the vertical value (Fig. 5a). In one crystal, all bromobenzene rings incline in the same direction with respect to the naphthalenedione ring. That is, only one handedness of 3 exists in one crystal. This chiral crystal is formed by the self-assembly of molecules of 3 through three types of interactions (Fig. 5b and c) [7]. One type is CH $-\pi$  interactions (2.63 Å, indicated by red A arrows in Fig. 5b), and the other is benzene-naphthalene edge-to-face interactions (2.88 Å, indicated by blue *B* arrows in Fig. 5b). Moreover, there are one CH–O hydrogen bond (2.60 Å. indicated by black C arrow in Fig. 5b) and one CH-S hydrogen bond (2.84 Å, indicated by black D arrow in Fig. 5b).

The crystal structure of **IIIB** obtained from the  $CH_2Cl_2$  solution is shown in Fig. 6.

It is composed of only **3** without the crystallization solvent. This crystal belongs to the achiral space group *P*–1. A characteristic feature of the structure is the presence of two independent molecules, **3a** and **3b**, which have different torsion angles around the sulfur atom in an asymmetric unit (Fig. 6a and b, indicated in blue color for **3a** and green color for **3b**). The torsion angles of these molecules are ±133.9° for **3a** [C(3)-C(2)-S(12)-C(13)] and ±124.6° for **3b** [C(23)-C(22)-S(32)-C(33)]. This achiral crystal is formed by the stacking of these molecules along the *a*-axis through  $\pi$ – $\pi$  interactions (indicated by the red circle, 3.46 and 3.66 Å, in Fig. 6d) [8]. Moreover, there are three CH–O hydrogen bonds (2.36, 2.59, and 2.56 Å, indicated by red *A*, blue *B*, and black *C* arrows, respectively, in Figs. 6c and 6d) and one CH–Br hydrogen bond (2.88 Å, indicated by black *D* arrow in Fig. 6c) [7].

For comparison, the crystal structure of **II** is shown in Fig. 7.

This crystal belongs to the achiral space group  $P2_1/n$ . The torsion angle is ±159.5° [C(3)-C(2)-S(12)-C(13)] (Fig. 7a). **2** forms a columnar unit (indicated by the red dotted rectangle in Fig. 7b) along the *c*-axis through CH– $\pi$  (2.80 Å, indicated by red *A* arrows in Fig. 7b) and CH–O hydrogen bond (2.39 Å, indicated by blue *B* arrow in Fig. 7b) interactions [7]. This achiral crystal is formed by the self-assembly of this columnar unit (indicated by the red dotted by the red dotted circle in Fig. 7c) through CH–O hydrogen bond (2.45 Å, indicated by black *C* arrows in Fig. 7c) [7].

The two conformational polymorphs of **3** showed different optical properties. Therefore, the difference in the colors of crystals IIIA and **IIIB** may be attributed to the different conformations or packing arrangements of 3 in these crystals. To verify this, excited states of the molecules in IIIA and IIIB were calculated by the ZIN-DO method [9,10]. The excitation energies of **3** in **IIIA** were calculated as 2.58, 2.63, 3.62, 4.07, and 4.12 eV, and those in IIIB were calculated as 2.59, 2.67, 3.66, 4.11, and 4.15 eV. These values indicate that the conformational polymorphs of 3 in IIIA and IIIB should have similar energy absorption; however, the DRS spectra indicate that the latter has lower energy absorption than the former (Fig. 3). Therefore, the reason for the difference in the colors of IIIA and IIIB can not be explained simply on the basis of the molecular geometry. It is likely that the excited states of 3 are affected rather strongly by the intermolecular interactions in these crystals.

In order to study the control of polymorphism and examine the reversible switching between the two conformational polymorphs (**IIIA** and **IIIB**) in bulk products, the polymorphism of **3** was investigated by X-ray powder diffraction (XRPD) analyses. When crystals **IIIA** were dissolved in the  $CH_2Cl_2$  solution and crystallized,



**Fig. 5.** Crystal structure of **IIIA**. Oxygen and sulfur atoms are shown in red and orange, respectively. (a) Structure of extracted single molecule **3.** (b) Packing structure observed along the *a*-axis. (c) Packing structure observed along the *b*-axis. Red *A*, blue *B*, and black *C* (or *D*) arrows indicate CH–π, benzene-naphthalene edge-to-face, and hydrogen bond interactions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** Crystal structure of **IIIB**. Oxygen and sulfur atoms are shown in red and orange, respectively. (a) Structure of extracted single molecule **3a**. (b) Structure of extracted single molecule **3b**. (c) Packing structure observed along the *b*-axis. Red *A*, blue *B*, and black *C* (or *D*) arrows indicate hydrogen bond interactions. (d) Packing structure observed along the *a*-axis. The red circle shows a  $\pi$ - $\pi$  interaction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reddish purple crystals were obtained from the solution. XRPD patterns of these crystals showed that they were the same as crystals **IIIB** (Fig. 8). In the same way, when crystals **IIIB** were dissolved in the diethyl ether solution and crystallized, orange crystals identical to crystals **IIIA** were obtained from the solution (Fig. 8). Moreover, the rotational barrier for the dione ring of **3** around the thioether bond is calculated as 4.5 kcal/mol by the RHF method using the 6–31G basis set [11]. These results show that the polymorphism of this system can be perfectly and reversibly controlled by changing the crystallization conditions.

During crystallization from solution, **3** is crystallized through intermolecular interactions with the crystallization solvent. In particular, two carbonyl groups of **3** interact with the crystallization solvent. It is thought that the steric difference between the aryl ring and the 1,4-naphthoquinone ring may be the cause for the chiral crystallization of **3**.



**Fig. 7.** Crystal structure of **II**. Oxygen and sulfur atoms are shown in red and orange color, respectively. (a) Structure of extracted single molecule **2**. (b) Packing structure of columnar unit of **2** along the *c*-axis. (c) Packing structure of columnar unit observed along the *c*-axis. Red *A* arrows show CH–π interactions. Blue *B* and black *C* arrows indicate hydrogen bond interactions. Red dotted rectangle and circle show a columnar unit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 8. XRPD spectra of crystals IIIA and IIIB. (a) X-ray powder diffraction pattern of crystals. (b) Simulated X-ray powder pattern of the crystals, calculated from the crystal structure data.

#### 4. Conclusions

We found that the achiral compound 2-methyl-3-(4-bromophenylthio)-1,4-naphthalenedione has two conformational and color polymorphs. These polymorphs show different optical properties and the relationship between the two can be controlled by changing the crystallization conditions. In particular, by crystallization from the diethyl ether solution, this compound shows chirality in the crystalline state without any external chiral source. In the 2methyl-3-arylthio-1,4-naphthalenedione system, the relationship between chirality and color in the two polymorphs can be controlled by the type of arylthio group. 2-methyl-3-(2-naphthalenylthio)-1,4-naphthalenedione has achiral deep orange crystals and chiral reddish purple crystals. On the other hand, 2-methyl-3-(4bromophenylthio)-1,4-naphthalenedione has chiral deep orange crystals and achiral reddish purple crystals. We believe that the results of this study will be useful for the systematic design of a novel organic compound that shows conformational and color polymorphism.

# Acknowledgements

This work was supported by a Grant-in-Aid for Scientific Research (No. 22750133) from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and a research Grant from TEPCO Research Foundation. T.K. is grateful to JSPS Research Fellowships for Young Scientists.

# Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molstruc.2010.07.032.

#### References

- [1] [1a] J. Bernstein, Polymorphism in Molecular Crystals, Clarendon, Oxford, 2002;
   (b) N. Sanz, P.L. Baldeck, J.F. Nicoud, Y.L. Fur, A. Ibanez, Solid State Sci. 3 (2001) 867–875;
  - (c) L. Yu, J. Phys. Chem. A. 106 (2002) 544-550;
  - (d) P. Vishweshwar, J.A. McMahon, M. Oliveira, M.L. Peterson, M.J. Zaworotko, J. Am. Chem. Soc. 127 (2005) 16802–16803;
  - (e) T. Mutai, H. Satou, K. Araki, Nat. Mater. 4 (2005) 685-687;
  - (f) D.E. Braun, T. Gelbrich, R.K.R. Jetti, V. Kahlenberg, S.L. Price, U. Griesser, Cryst. Growth & Des. 8 (2008) 1977–1989. and references cited therein.
- [2] Y. Imai, T. Kinuta, K. Nagasaki, T. Harada, T. Sato, N. Tajima, Y. Sasaki, R. Kuroda, Y. Matsubara, CrystEngComm. 11 (2009) 1223–1225.
- [3] G.M. Sheldrick, Acta Crystallogr. Sec. A 64 (2008) 112-122.
- [4] A.L. Spek, PLATON, Molecular Geometry and Graphics Program, University of Utrecht, The Netherlands;, 1999.
- [5] G.M. Sheldrick, SADABS, Program for Empirical Absorption Correction of Area Detector Data. University of Gottingen, Germany, 1996

- [6] L.F. Fieser, R.H. Brown, J. Am. Chem. Soc. 71 (1949) 3609-3614.
- [7] It is determined by PLATON geometry calculation.
- [8] Distance between the nearest centers of intermolecular 6-membered rings of **3**.
- [9] (a) J.E. Ridley, M.C. Zerner, Theor. Chim. Acta 32 (1973) 111–134;
  (b) J.E. Ridley, M.C. Zerner, Theor. Chim. Acta 42 (1976) 223–236;
  (c) M.C. Zerner, G.H. Lowe, R.F.U.T. Kirchner Mueller-Westerhoff, J. Am. Chem. Soc. 102 (1980) 589–599.
- [10] The calculations have been performed using the Gaussian 03 program. Gaussian 03, Revision C.02, M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, J.A. Montgomery Jr, T. Vreven, K.N. Kudin, J.C. Burant, J.M. Millam, S.S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G.A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J.E. Knox, H.P. Hratchian, J.B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A.J. Austin, R. Cammi, C. Pomelli, J.W. Ochterski, P.Y. Ayala, K. Morokuma, G.A. Voth, P. Salvador, J.J. Dannenberg, V.G. Zakrzewski, S. Dapprich, A.D. Daniels, M.C. Strain, O. Farkas, D.K. Malick, A.D. Rabuck, K. Raghavachari, J.B. Foresman, J.V. Ortiz, Q. Cui, A.G. Baboul, S. Clifford, J. Cioslowski, B.B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R.L. Martin, D.J. Fox, T. Keith, M.A. Al-Laham, C.Y. Peng, A. Nanayakkara, M. Challacombe, P.M.W. Gill, B. Johnson, W. Chen, M.W. Wong, C. Gonzalez, J. A. Pople, Gaussian, Inc., Wallingford CT, 2004.
- [11] W.J. Hehre, R. Ditchfield, J.A. Pople, J. Chem. Phys. 56 (1972) 2257-2261.