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# X-ray crystallographic analysis of *N*,*N*-diallylcoumarincarboxamides and the solid-state photochemical reaction

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**Abstract**—X-ray crystallographic analysis and the photochemical aspects of *N*,*N*-diallylcoumarincarboxamides were investigated. Irradiation of the corresponding amides promoted stereoselective intramolecular cyclobutane formation exclusively. The solid-state photoreaction of the coumarinamide without substituent on the 4-position proceeded in a crystal-to-crystal manner. On the other hand, photolysis of the amide possessing a methyl group at the 4-position also effected 2+2 cycloaddition; however, the reaction proceeded much slower. The difference in the reactivity was explainable on the basis of the molecular conformation in the crystal lattice.

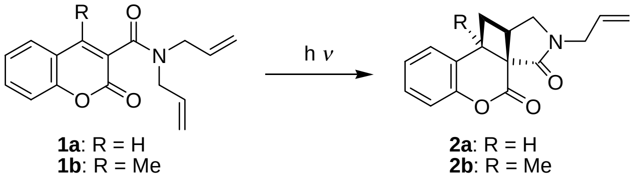
## 1. Introduction

Solid-state photoreaction provides product- and stereoselectivity compared to reactions that occur in solution due to restriction of molecular movement imposed by the environment.[1] Many examples are reported of topochemical intermolecular 2+2 cyclobutane formation of alkenes, and the geometrical studies are well-known as Schmidt's rule, which means that the reactive alkenyl groups locate within 4.2 Å of the center-to-center distance in parallel to promoted cycloaddition.[2] Compared to a large amount of data for intermolecular cycloaddition reactions,[3] there is little information on intramolecular reactions.[4] Intermolecular reactions are strongly affected by the molecular arrangement in the crystal; on the other hand, molecular conformation in the ground-, excited- and transition-state also plays an important role in the intramolecular photoprocess. To investigate the geometrical aspects of intramolecular 2+2 photocycloaddition and the difference between photochemical reactivity with the reaction media, photochemical reaction of *N*,*N*-diallylcoumarin-3-carboxamides was examined, because coumarin is well-known as not only one of the photoreactive molecules for dimerization and 2+2 cycloaddition with alkenes,[5] but also natural products and biologically active materials.[6] Now we have found that *N*,*N*-diallylcoumarin-3-caboxamides showed effective photochemical reactivity and gave cylobutanes selectively, and one of the reactions proceeded in a crystal-to-crystal manner.

## 2. Results and discussion

*N*,*N*-Diallylcoumarin-3-carboxamide **1a** and the 4-methyl derivative **1b** were conveniently prepared from the

**Table 1**. Photochemical reaction of *N*,*N*-diallylcoumarincarboxamides **1**



| Entry | Amide **1** | Conditions[a] | Conversion (%) | Yield (%) of **2**[b] |
|---|---|---|---|---|
| 1 | **1a** | Benzene (5 h)[c] | 100 | 98 |
| 2 | **1a** | Solid-state (2 h) | 100 | 100 |
| 3 | **1b** | Benzene (12 h)[c] | 47 | 50 |
| 4 | **1b** | Solid-state (6 h) | 46 | 100 |
| 5 | **1b** | Solid-state (12 h) | 99 | 74 |

[a] A 0.02 M benzene solution in a Pyrex vessel under argon was irradiated with a 500 W high pressure mercury lamp.

[b] Chemical yields were determined on the basis of consumed coumarins.

[c] Number in parentheses is irradiation time.

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*Keywords*: Coumarincarboxamide derivatives; Solid-state reaction; 2+2 Cycloaddition; X-ray crystallography; Photochemical reaction.

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corresponding carboxylic acids (Table 1).[7] Recrystallization of the amide **1a** from a mixture of chloroform and hexane gave colorless plates, and **1b** afforded colorless needles. Both amides were subjected to X-ray single crystal analysis, and Figure 1 shows the ORTEP view of the amides **1a–b**. Each amide plane twisted almost orthogonally to the coumarin chromophore, and the torsion resulted in closed orientation of the reacting alkenyl bonds.

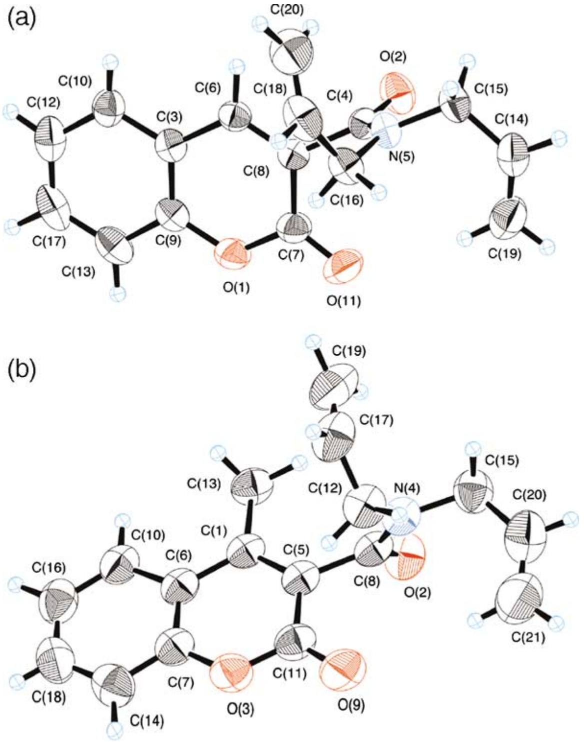


**Figure 1.** (a) ORTEP view of **1a**. (b) ORTEP view of **1b**.

When a 0.02 M benzene solution of the amide **1a** was irradiated with a 500 W high-pressure mercury lamp under argon atmosphere, intermolecular 2+2 photocyclization proceeded and multi-cyclic cyclobutane **2a** was obtained in 98% yield (Table 1, entry 1). The structure of **2a** was determined on the basis of its spectral data. Finally, the structure was unequivocally established by single crystal X-ray crystallographic analysis (Fig. 2).

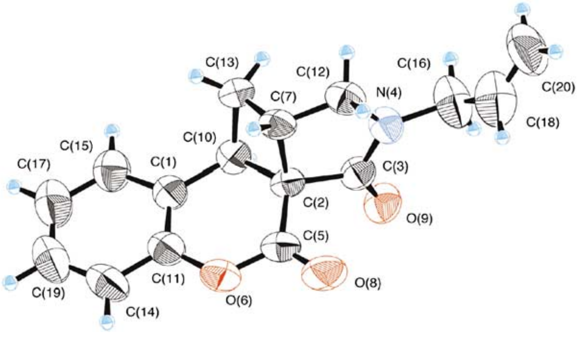


**Figure 2.** ORTEP view of the photoproduct **2a**.

When the powdered crystals of **1a** were irradiated, the solid-state photoreaction proceeded more effectively than the reaction in solution (Table 1, entries 1–2). Furthermore, the crystal-to-crystal behavior was confirmed on the basis of the X-ray powder diffraction as shown in Figure 3. Figure 3a shows the spectrum of starting material **1a**; Figure 3b exhibited the reflection pattern of 100% conversion yield, and still shows sharp reflections. Figure 3c, derived from recrystallized **2a** shows almost same reflections as Figure 3b. We attempted a single crystal X-ray analysis of the photolyzed crystals; however, sufficient reflections for the analysis were not obtained.

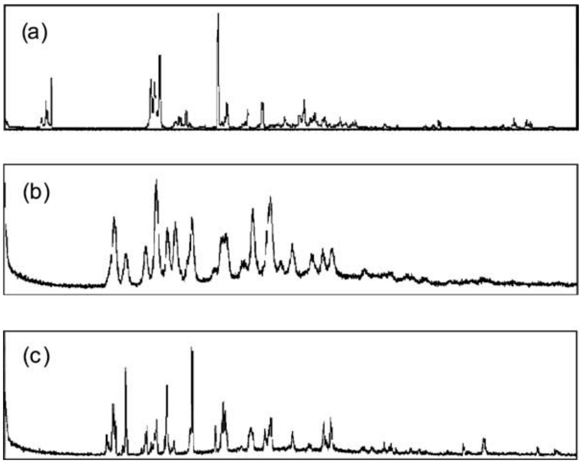


**Figure 3.** X-ray diffraction pattern for the transformation of **1a** to **2a**. (a) Starting material **1a**. (b) Irradiated crystals at 100% conversion. (c) Recrystallized **2a** from $CHCl_3$–hexane solution.

In the case of **1b**, photolysis of a 0.02 M benzene solution gave the corresponding cyclobutane **2b** in 50% yield accompanied by a complex mixture (Table 1, entry 3). Decreasing the concentration to 0.01 M did not improve the chemical yield. On the other hand, when the powdered crystals of **1b** were irradiated, a chemoselective reaction occurred and only cyclobutane **2b** was isolated. However, the reaction was slower than that of **1a**; furthermore, the solid gradually became amorphous by prolonged irradiation, The solid melts down after 6 h of irradiation; cyclobutane **2b** was formed in 100% yield (46% conversion yield) at this point (entry 4). Prolonged irradiation resulted in decreasing the chemical yield of **2b** (entry 5), because of the formation of a complex mixture. Figure 4a shows the XRD pattern of **1b**, and Figure 4b exhibits those of 46% conversion yield, which shows that the reflections derived from **1b** decreased with no new reflection. In all cases, no coumarin dimer was detected at all.

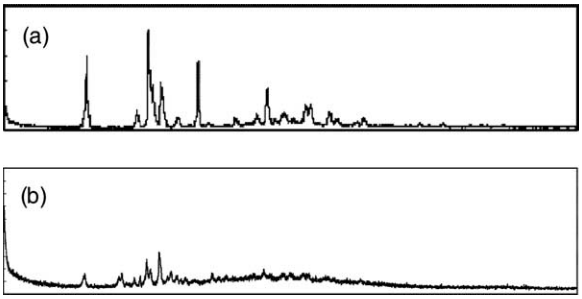


**Figure 4.** X-ray diffraction pattern for the transformation of **1b** to **2b**. (a) Starting material **1b**. (b) Transition pattern (irradiated for 6 h, 46% conversion).

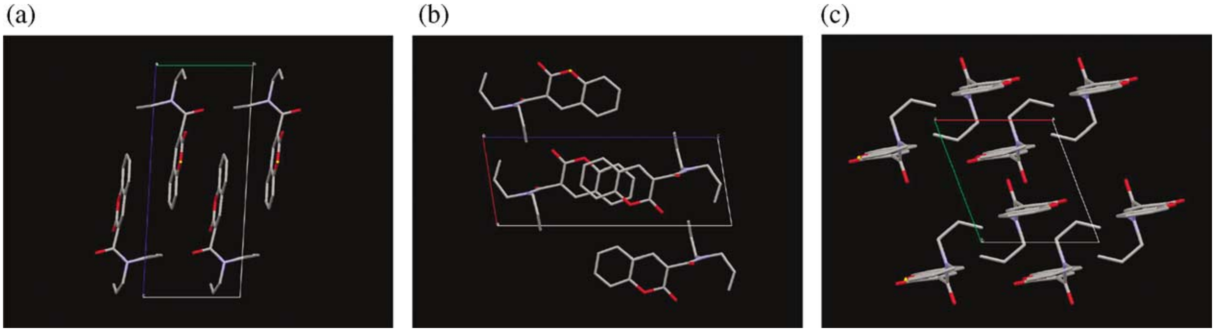


**Figure 5.** Packing diagram of **1a**. (a) A view from *a*-axis. (b) A view from *b*-axis. (c) A view from *c*-axis.

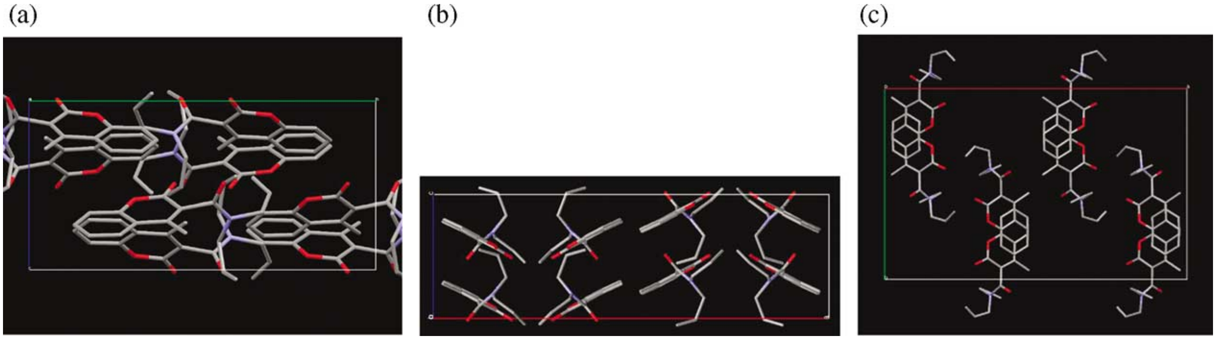
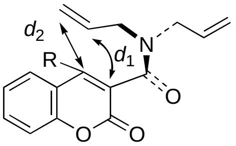


**Figure 6.** Packing diagram of **1b**. (a) A view from *a*-axis. (b) A view from *b*-axis. (c) A view from *c*-axis.

In both cases, the solid-state irradiation did not give coumarin dimer but yielded cyclobutane via intramolecular cycloaddition. Matsuura and Venkatesan independently reported photodimerization of coumarin derivatives in the solid-state.[5a,d] In Venkatesan's case, the distance between each reacting alkenyl bond was 3.81–3.87 Å, which is much shorter than the Schmidt's rule, <4.2 Å. In the cases of **1a** and **1b**, photodimerization was not observed and effective intramolecular cycloaddition occurred exclusively. The packing diagram clearly indicates the reason for their reactivities. Figures 5 and 6 show the packing image of **1a** and **1b**, respectively. In both cases, planes of coumarin make parallel position in the crystal; however, the reacting double bonds were placed far away. In the case of **1a**, the center-to-center distance was 7.0 Å, and 5.1 Å for **1b**; their value was over 4.2 Å.

The conformational factor plays a very important role in the intramolecular cycloaddition reaction in the solid-state reaction, because interconversion involving a dramatic movement of the atoms cannot usually occur. Table 2 shows the distances between each reacting alkenyl carbon atom. In the case of **1a**, the reaction proceeded retaining the crystallinity, where both reacting carbon atoms are placed closely, 3.59 and 3.83 Å for $d_1$ and $d_2$, respectively. Then the C–C bond formation leading to a cyclobutane ring does not need drastic atomic reorientation. However, the reaction of **1b** occurred rather more slowly than that of **1a**, and the solid changed to amorphous according to the progress of the reaction. The fact is reasonably explainable on the basis of the molecular conformation of which the $d_2$ value for **1b** exceeds 4.2 Å. This is because of the steric repulsion between the methyl group at the 4-position and the allyl group, which keep away each reacting double bond. Furthermore, the formation of cyclobutane, in which the sp$^2$ carbon atom at the C4 position transformed to sp$^3$ hybridization, needs considerably dramatic movement of the methyl group at the C4 position. The difference in photochemical reactivity was explainable on the basis of the molecular conformation in the crystal lattice.

**Table 2**. Distances between the reacting carbon atoms



| Coumarin | Distance (Å) | |
|---|---|---|
| | $d_1$ | $d_2$ |
| **1a** | 3.59 | 3.83 |
| **1b** | 3.68 | 4.21 |

In conclusion, when *N*,*N*-diallylcoumarin-3-carboxamides were irradiated in solution and in the solid-state. The stereoselective cyclobutane formation was observed because of the reacting alkenyl group was placed intramolecularly, and was proceeded more effectively than the dimerization of coumarin chromophore. Whereas the solid-state photolysis of the coumarincarboxamide with a methyl group at the 4-position afforded an amorphous compound according to the progress of the reaction, that of the corresponding amide with no substituent gave quantitative yield of cyclobutane, where the crystallinity was maintained after 100% conversion, and the crystal-to-crystal manner was confirmed by XRD analysis. This reaction provides a fine example of stereo-controlled intramolecular photocycloaddition reaction of hetero aromatics.

## 3. Experimental

NMR spectra were recorded on $CDCl_3$ solutions on a BRUKER 300 operating 300 MHz, respectively, for $^1H$ and $^{13}C$ NMR spectroscopy. Chemical shifts are reported in parts per million (ppm) relative to TMS as internal standards. UV spectra were measured with a JASCO model V-570 UV/VIS/NIR spectrophotometer. IR spectra were recorded on a JASCO FT/IR-230 spectrometers as KBr disks, unless otherwise noted.

### 3.1. General procedure for the preparation of *N*,*N*-diallylcoumarincarboxamides 1a and 1b

Both coumarincarboxamides **1a–1b** were provided from corresponding coumarincarboxylic acid[7] and diallyl amine. A synthesis of **1a** was exemplified as follows. To a toluene solution containing 1.5 g (5.5 mmol) of coumarincarboxylic acid and triethylamine 0.80 g (8.0 mmol) was added 0.79 g (6.6 mmol) of thionyl chloride at 0 °C. The reaction mixture was stirred for 0.5 h, and then diallylamine 1.4 g (14.0 mmol) was added dropwise. After the reaction mixture was stirred for 1 h, water was added, and extracted as a usual manner. After toluene was evaporated in vacuo and the residual mixture was subjected to chromatography on silica gel and the crystalline amide **1a** was recrystallized from ethanol; afforded colorless plates. The structures of **1a** and **1b** were determined on the basis of spectral data, mass spectroscopy, and unequivocally X-ray crystallographic analyses.

**3.1.1. *N*,*N*-Diallylcoumarincarboxamides 1a.** The title compound was obtained colorless plates from ethanol; mp 127–129 °C; IR ($cm^{-1}$, KBr) 1631, 1712; $^1H$ NMR ($CDCl_3$) $\delta$ 3.87 (d, $J=5.6$ Hz, 2H, $CH_2$), 4.15 (d, $J=5.4$ Hz, 2H, $CH_2$), 5.14–5.36 (m, 4H, $2\times C{=}CH_2$), 5.78–5.84 (m, 2H, $2\times CH{=}CH_2$), 7.28–7.38 (m, 2H, Ar*H*), 7.51–7.59 (m, 2H, Ar*H*), 7.83 (s, 1H, 4-C*H*); $^{13}C$ NMR 47.2, 51.2, 117.2, 118.3, 118.6, 125.3, 125.9, 128.9, 132.2, 133.1, 133.4, 142.3, 154.4, 158.5, 165.4; HR-MS (FAB). Anal. 270.1130 Calcd for $C_{16}H_{15}NO_3$ ($MH^+$). Found: *m/z* 270.1124 ($MH^+$).

*X-ray crystallographic data of* **1a**. Triclinic space group *P*-1, $a=6.516(2)$ Å, $b=7.101(3)$ Å, $c=16.027(4)$ Å, $\alpha=89.93(3)°$, $\beta=81.48(2)°$, $\gamma=69.12(3)°$, $V=684.1(4)$ Å$^3$, $Z=2$, $\rho=1.307$ g/cm$^3$, $\mu$(Cu K$\alpha$)$=0.74$ mm$^{-1}$. The structure was solved by the direct method of full-matrix least-squares, where the final *R* and *Rw* were 0.051 and 0.226 for 2345 reflection. CCDC 268496 contains crystallographic data. These crystallographic data can be obtained free of charge via www.ccdc.cam.ac.uk (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033 (e-mail: deposit@ccdc.cam.ac.uk).

**3.1.2. *N*,*N*-Diallyl-4-methylcoumarincarboxamides 1b.** The title compound was obtained colorless needles from a mixture of $CHCl_3$–hexane; mp 85–87 °C; IR ($cm^{-1}$, KBr) 1630, 1714; $^1H$ NMR ($CDCl_3$) $\delta$ 2.44 (s, 3H, $CH_3$), 3.85 (d, $J=5.8$ Hz, 2H, $CH_2$), 4.14–4.25 (m, 2H, $CH_2$), 5.10–5.38 (m, 4H, $2\times C{=}CH_2$), 5.69–5.78 (m, 1H, $CH{=}CH_2$), 5.83–5.91 (m, 1H, $CH{=}CH_2$), 7.30–7.38 (m, 2H, Ar*H*), 7.51–7.59 (m, 1H, Ar*H*), 7.64–7.68 (m, 1H, Ar*H*); $^{13}C$ NMR 16.7, 46.9, 51.2, 117.5, 118.4, 119.1, 119.9, 124.0, 125.1, 125.5, 132.4, 132.7, 133.3, 149.4, 153.3, 158.6; HR-MS (FAB). Anal. 284.1287 Calcd for $C_{17}H_{17}NO_3$ ($MH^+$). Found: *m/z* 284.1275 ($MH^+$).

*X-ray crystallographic data of* **1b**. Orthorhombic space group *Pbca*, $a=24.705(9)$ Å, $b=15.742(6)$ Å, $c=7.728(4)$ Å, $V=3005.0(2)$ Å$^3$, $Z=8$, $\rho=1.252$ g/cm$^3$, $\mu$(Cu K$\alpha$)$=0.70$ mm$^{-1}$. The structure was solved by the direct method of full-matrix least-squares, where the final *R* and *Rw* were 0.056 and 0.180 for 1712 reflections, CCDC 268497 contains crystallographic data.

### 3.2. General procedure for the photochemical reaction in benzene

A benzene solution of amides **1a–1b** (0.02 M) was purged with deoxygenated and dried argon for 15 min prior to photolysis and was irradiated with a 500-W Eikosha high-pressure mercury lamp through a Pyrex filter. After irradiation, benzene was evaporated and the photolysate was chromatographed on silica gel (Merk Kieseigel 60) with ethyl acetate–hexane (10/1) as the eluent.

### 3.3. General procedure for the photochemical reaction in the solid-state

Solid samples were irradiated as a powder sandwiched between Pyrex glasses in the inside of a polyethylene bags and was fixed out side of a emersion well apparatus. After irradiation, the photolysate was treated as same as that in solution photochemistry.

**3.3.1. Photoproduct 2a.** The title compound was obtained colorless prisms from a mixture of $CHCl_3$–hexane; mp 162–163 °C; IR ($cm^{-1}$, KBr) 1691, 1745; $^1H$ NMR ($CDCl_3$) $\delta$ 2.37–2.66 (m, 2H, $CH_2$), 3.23 (d, $J=10.5$ Hz, 1H, C*H*), 3.44 (dd, $J=22.4$, 7.8 Hz, 1H, C*H*), 3.68 (m, 1H, C*H*), 3.92, (d, $J=6.2$ Hz, 1H, C*H*), 3.97–4.18 (m, 2H, C*H*), 5.28–5.37 (m, 2H, $C{=}CH_2$), 5.77–5.88 (m, 1H, $CH{=}C$), 7.04–7.30 (m, 4H, Ar*H*); $^{13}C$ NMR 35.2, 36.5, 37.2, 46.2, 51.9, 52.1, 118.0, 119.2, 123.5, 125.9, 128.6, 129.2, 131.9, 150.4, 164.6, 171.1; HR-MS (FAB). Anal. 270.1130 Calcd for $C_{16}H_{16}NO_3$ ($MH^+$). Found: *m/z* 270.1124 ($MH^+$).

*X-ray crystallographic data of* **2a**. Orthorhombic space group *Pbca*, $a=16.019(3)$ Å, $b=15.451(3)$ Å, $c=10.799(3)$ Å, $V=2672.7(10)$ Å$^3$, $Z=8$, $\rho=1.339$ g/cm$^3$, $\mu$(Cu K$\alpha$)$=0.76$ mm$^{-1}$. The structure was solved by the direct method of full-matrix least-squares, where the final *R* and *Rw* were 0.058 and 0.119 for 2881 reflections, CCDC 268498 contains crystallographic data.

**3.3.2. Photoproduct 2b.** The title compound was obtained colorless prisms from a mixture of $CHCl_3$–hexane; mp 80–82 °C; IR ($cm^{-1}$, KBr) 1685, 1750; $^1H$ NMR ($CDCl_3$) $\delta$ 1.54 (s, 3H), 2.18–2.24 (dd, $J=8.0$, 12.0 Hz, 1H), 2.55–2.62 (dd, $J=8.5$, 12.0 Hz, 1H), 3.16–3.24 (m, 1H), 3.58–3.64 (m, 1H), 3.91–3.98 (m, 1H), 4.20–4.27 (m, 2H), 5.27–5.36 (m, 2H), 5.77–5.88 (m, 1H), 7.03–7.06 (m, 1H), 7.21–7.30 (m, 3H); $^{13}C$ NMR 27.2, 34.0, 41.8, 42.6, 46.1, 51.8, 56.1, 118.0, 119.0, 126.0, 119.1, 126.0, 127.7, 128.6, 129.2, 132.2, 149.4, 169.5; HR-MS (FAB). Anal. 284.1287 Calcd for $C_{17}H_{18}NO_3$ ($MH^+$). Found: *m*/*z* 284.1274 ($MH^+$).

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