ISSN 1070-4280, Russian Journal of Organic Chemistry, 2016, Vol. 52, No. 10, pp. 1537–1539. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © A.S. Bunev, E.S. Belinskaya, N.N. Gryzunova, A.A. Vikarchuk, 2016, published in Zhurnal Organicheskoi Khimii, 2016, Vol. 52, No. 10, pp. 1542–1544.

SHORT COMMUNICATIONS

Copper(II) Oxide Nanowhiskers—A New Efficient Catalyst of Azide–Alkyne Cycloaddition

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Received February 1, 2016

DOI: 10.1134/S1070428016100328

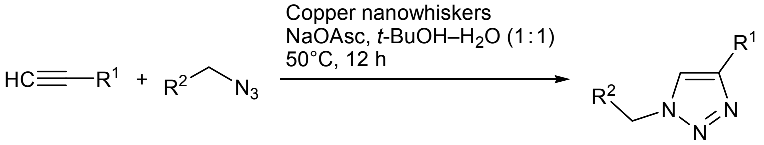
At the beginning of the XXI century, much attention has been given to environmentally benign processes with the use of highly efficient catalysts [1–3]. Among numerous transition metal compounds, copper catalysts have been most needed during the past decade [4–7]. The discovery of azide–alkyne cycloaddition catalyzed by copper salts, which selectively affords 1,4-disubstituted 1,2,3-1*H*-triazoles, has opened new perspectives in the 1,2,3-triazole chemistry [8, 9]. It is known that 1,2,3-1*H*-triazole derivatives are important building blocks for the synthesis of nitrogen-containing heterocycles and are widely used in pharmaceutical industry and agricultural chemistry [10, 11]. The following compounds should be noted among efficient copper catalysts of the azide–alkyne cycloaddition: $CuSO_4$ [12–14], Cu_2O [15], CuI [16, 17], $(Ph_3P)_2CuBr$ [18], copper nanoparticles [19], $CuFe_2O_4$ [1], Cu/SiO_2 [20], Cu/S [21], and Cu/Cu_2O [22].

Herein we present the results of studying the catalytic activity of nanosized whiskers (filamentary crystals) in the azide–alkyne cycloaddition. We previously reported a new form of copper(II) oxide, nanosized whiskers [23]. According to the low-temperature krypton desorption data, the obtained catalyst was characterized by a high specific surface area (81 m^2/g). The average diameter of copper oxide nanowhiskers ranged from 40 to 120 nm, and their length was up to 100 nm. The X-ray powder diffraction data showed that copper nanowhiskers consist of three phases: coperr(II) oxide, copper(I) oxide, and copper metal [23].

The optimal conditions for the reaction of phenylacetylene (**1a**) with benzyl azide (**2a**) as model substrates were as follows: a mixture of **1a** and **2a** in aqueous *tert*-butyl alcohol was heated for 12 h at 50°C in the presence of 2 mol % of copper oxide nanowhiskers (calculated on Cu) and 20 mol % of sodium ascorbate as reducing agent necessary for the regeneration of the whisker surface consisting mainly of CuO. The yield of 1-benzyl-4-phenyl-1,2,3-1*H*-triazole (**3a**) attained 88% according to the ^1H NMR data.

The reactions of substituted acetylenes **1a**–**1c** with azides **2a**–**2f** under the optimal conditions afforded 1,4-disubstituted 1,2,3-1*H*-trizoles **3a**–**3j** in 87–93% yield. No relation between the substituent nature in the initial reactants and the product yield was observed.

The ^1H NMR spectra of **3a**–**3j** displayed a singlet at δ 7.50–7.91 ppm due to 5-H on the triazole ring, as well as signals from aromatic protons and substituents in the aromatic rings. The ^{13}C NMR spectra of **3a**–**3j** contained signals at δ_C 119.0–121.0 and 131.0–



1a–1c **2a–2f** **3a–3j**

1, R^1 = Ph (**a**), 4-MeC_6H_4 (**b**), $PhOCH_2$ (**c**); **2**, R^2 = Ph (**a**), 4-MeC_6H_4 (**b**), 4-$MeOC_6H_4$ (**c**), 4-FC_6H_4 (**d**), 4-$O_2NC_6H_4$ (**e**), CO_2Et (**f**); **3**, R^1 = Ph, R^2 = Ph (**a**), 4-MeC_6H_4 (**b**), 4-$MeOC_6H_4$ (**c**), 4-FC_6H_4 (**d**), 4-$O_2NC_6H_4$ (**e**); R^1 = 4-MeC_6H_4, R^2 = Ph (**f**), 4-MeC_6H_4 (**g**); R^1 = Ph, R^2 = CO_2Et (**h**); R^1 = 4-MeC_6H_4, R^2 = CO_2Et (**i**); R^1 = $PhOCH_2$, R^2 = Ph (**j**).

135 ppm (C^4, C^5), which indicated formation of exclusively 1,4-disubstituted 1,2,3-1*H*-triazoles.

General procedure for azide–alkyne cycloaddition. Copper oxide nanowhiskers (0.04 mmol of Cu), and a solution of 0.4 mmol of sodium ascorbate in 0.1 mL of water were added in succession to a mixture of 2 mmol of acetylene **1a**–**1c** and 2 mmol of azide **2a**–**2f** in 5 mL of aqueous *tert*-butyl alcohol (1 : 1). The mixture was stirred for 12 h at 50°C, and the precipitate was filtered off and dried in air.

1-Benzyl-4-phenyl-1*H*-1,2,3-triazole (3a). Yield 88%, mp 128–129°C; published data [24]: mp 127–128°C. ^{1}H NMR spectrum, δ, ppm: 5.57 s (2H, CH$_2$), 7.25–7.36 m (3H, H$_{arom}$), 7.37–7.41 m (5H, H$_{arom}$), 7.65 s (1H, 5-H), 7.80 d (2H, H$_{arom}$, J = 8.6 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 54.2, 119.4, 125.6, 128.0, 128.1, 128.7, 129.1, 130.5, 134.6, 148.2.

1-(4-Methylbenzyl)-4-phenyl-1*H*-1,2,3-triazole (3b). Yield 91%, mp 109–111°C; published data [24]: mp 110–112°C. ^{1}H NMR spectrum, δ, ppm: 2.35 s (3H, CH$_3$), 5.52 s (2H, CH$_2$), 7.17–7.21 m (4H, H$_{arom}$), 7.28–7.31 m (1H, H$_{arom}$), 7.38 d.d (2H, H$_{arom}$, J = 8.1, 1.8 Hz), 7.62 s (1H, 5-H), 7.79 d (2H, H$_{arom}$, J = 8.1 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 21.1, 54.0, 119.3, 125.6, 128.0, 128.1, 128.7, 129.7, 130.5, 131.6, 138.7, 148.1.

1-(4-Methoxybenzyl)-4-phenyl-1*H*-1,2,3-triazole (3c). Yield 93%, mp 125–127°C; published data [24]: mp 129–130°C. ^{1}H NMR spectrum, δ, ppm: 3.81 s (3H, OCH$_3$), 5.50 s (2H, CH$_2$), 6.92 d (2H, H$_{arom}$, J = 9.2 Hz), 7.25–7.32 m (3H, H$_{arom}$), 7.90 t (2H, H$_{arom}$, J = 7.5 Hz), 7.61 s (1H, 5-H), 6.79 d (2H, H$_{arom}$, J = 6.9 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 53.7, 55.3, 114.5, 119.2, 125.6, 126.6, 128.0, 128.1, 128.7, 129.6, 129.8, 130.5, 148.1, 159.9.

4-(4-Fluorobenzyl)-1-phenyl-1*H*-1,2,3-triazole (3d). Yield 89%, mp 154–155°C; published data [25]: mp 152–153°C. ^{1}H NMR spectrum, δ, ppm: 5.54 s (2H, CH$_2$), 7.07 t (2H, H$_{arom}$, J = 8.6 Hz), 7.29–7.33 m (3H, H$_{arom}$), 7.40 t (2H, H$_{arom}$, J = 7.5 Hz), 7.65 s (1H, 5-H), 7.80 d (2H, H$_{arom}$, J = 8.1 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 53.4, 116.1, 119.2, 119.3, 125.7, 128.3, 128.7, 128.8, 129.7, 129.8, 130.0, 130.4, 130.5, 148.3, 161.8.

1-(4-Nitrobenzyl)-4-phenyl-1*H*-1,2,3-triazole (3e). Yield 92%, mp 85–86°C; published data [25]: mp 91°C. ^{1}H NMR spectrum, δ, ppm: 5.69 s (2H, CH$_2$), 7.31–7.36 m (1H, H$_{arom}$), 7.40–7.44 m (4H, H$_{arom}$), 7.76 s (1H, 5-H), 7.81 d (2H, H$_{arom}$, J = 6.9 Hz), 8.22 d (2H, H$_{arom}$, J = 6.9 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 53.1, 119.7, 124.0, 124.2, 125.7, 128.4, 128.5, 128.8, 130.0, 141.7, 148.0, 148.6.

1-Benzyl-4-(4-methylphenyl)-1*H*-1,2,3-triazole (3f). Yield 92%, mp 153–155°C. ^{1}H NMR spectrum, δ, ppm: 2.35 s (3H, CH$_3$), 5.55 s (2H, CH$_2$), 7.20 d (2H, H$_{arom}$, J = 8.0 Hz), 7.26–7.30 m (2H, H$_{arom}$), 7.35–7.40 m (3H, H$_{arom}$), 7.61 s (1H, 5-H), 7.68 d (2H, H$_{arom}$, J = 8.1 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 21.2, 54.1, 119.1, 125.5, 127.7, 128.0, 128.7, 129.0, 129.4, 134.7, 127.9, 148.2. Found, %: C 77.11; H 6.10; N 16.91. C$_{16}$H$_{15}$N$_3$. Calculated, %: C 77.08; H 6.06; N 16.85.

1-(4-Methylbenzyl)-4-(4-methylphenyl)-1*H*-1,2,3-triazole (3g). Yield 91%, mp 118–119°C; published data [25]: mp 120–121°C. ^{1}H NMR spectrum, δ, ppm: 2.35 s (6H, CH$_3$), 5.50 s (2H, CH$_2$), 7.17–7.25 m (6H, H$_{arom}$), 7.58 s (1H, 5-H), 7.67 d (2H, H$_{arom}$, J = 8.0 Hz). ^{13}C NMR spectrum, δ$_C$, ppm: 21.1, 21.2, 53.9, 118.9, 125.5, 127.7, 128.0, 129.4, 129.7, 131.6, 137.9, 138.6, 148.1. Found, %: C 77.59; H 6.55; N 15.99. C$_{17}$H$_{17}$N$_3$. Calculated, %: C 77.54; H 6.51; N 15.96.

Ethyl 2-(4-phenyl-1*H*-1,2,3-triazol-1-yl)acetate (3h). Yield 87%, mp 94–95°C; published data [26]: mp 92–93°C. ^{1}H NMR spectrum, δ, ppm: 1.31 t (3H, CH$_3$, J = 7.5 Hz), 4.29 q (2H, CH$_2$, J = 7.4 Hz), 5.20 s (2H, CH$_2$), 7.32–7.36 m (1H, H$_{arom}$), 7.43 t (2H, H$_{arom}$, J = 7.5 Hz), 7.85 d (2H, H$_{arom}$, J = 8.0 Hz), 7.91 s (1H, 5-H). ^{13}C NMR spectrum, δ$_C$, ppm: 14.0, 50.9, 62.4, 120.9, 125.8, 128.2, 128.8, 130.3, 148.2, 166.2.

Ethyl 2-[(4-methylphenyl)-1*H*-1,2,3-triazol-1-yl]-acetate (3i). Yield 89%, mp 100–102°C; published data [26]: mp 99–101°C. ^{1}H NMR spectrum, δ, ppm: 1.30 t (3H, CH$_3$, J = 7.4 Hz), 2.38 s (6H, CH$_3$), 4.28 q (2H, CH$_2$, J = 6.9 Hz), 5.18 s (2H, CH$_2$), 7.24 d (2H, H$_{arom}$, J = 8.1 Hz), 7.74 d (2H, H$_{arom}$, J = 8.0 Hz), 7.86 s (1H, 5-H). ^{13}C NMR spectrum, δ$_C$, ppm: 14.0, 21.2, 50.9, 62.4, 120.5, 125.7, 127.5, 129.4, 138.1, 148.3, 166.2. Found, %: C 63.73; H 6.21; N 17.20. C$_{13}$H$_{15}$N$_3$O$_2$. Calculated, %: C 63.66; H 6.16; N 17.13.

1-Benzyl-4-(phenoxymethyl)-1*H*-1,2,3-triazole (3j). Yield 93%, mp 126–127°C; published data [24]: mp 128–129°C. ^{1}H NMR spectrum, δ, ppm: 5.15 s (2H, CH$_2$), 5.49 s (2H, CH$_2$), 6.89–6.93 m (3H, H$_{arom}$), 7.21–7.26 m (4H, H$_{arom}$), 7.29–7.34 m (3H, H$_{arom}$), 7.50 s (1H, 5-H). ^{13}C NMR spectrum, δ$_C$, ppm: 54.5, 62.2, 115.0, 121.5, 122.8, 128.3, 129.0, 129.4, 129.8, 134.7, 144.9, 158.4.

The ^{1}H and ^{13}C NMR spectra were recorded on a Bruker Avance spectrometer at 600 and 150 MHz, respectively, using DMSO-d_6 as solvent and tetramethylsilane as internal standard. The elemental analyses were obtained with a Vario El cube analyzer. The melting points were measured on a Boetius hot stage and are uncorrected. The procedure for the preparation of copper(II) oxide nanowhiskers was described in [23].

Acetylene **1c** [27] and azides **2a**–**2f** [28] were synthesized according to known methods. The other reagents were commercial products (from Acros Organics).

This study was performed under financial support by the Ministry of Education and Science of the Russian Federation (project no. 14.V25.31.0011).

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