Capture of 3-Amino-4-oxycyanofurazan and Characterization of Isoxazole Product

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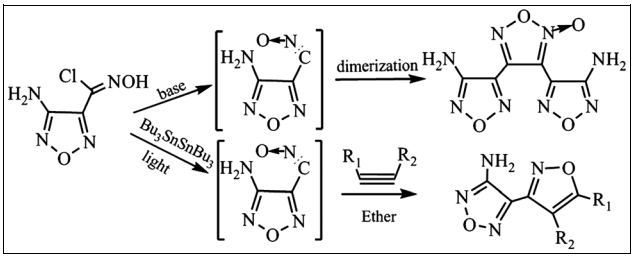
Received August 25, 2010
DOI 10.1002/jhet.842
Published online 14 February 2013 in Wiley Online Library (wileyonlinelibrary.com).



1,3-Dipolar cycloaddition reaction between nitrile oxide and alkyne was used to capture 3-amino-4-oxycyanofurazan (AOCF), which was considered as the key intermediate during the synthesis of 3,4-bis (4-aminofurazano-3-yl)furoxan (DATF) from 3-amino-4-chloroximinofurazan. The isolated isoxazoles from the reaction afforded evidences for the existence of AOCF. The structures of the isoxazoles were characterized by IR, ^{1}H NMR, ^{13}C NMR, MS, and elemental analysis. In addition, single crystal X-ray diffraction of one isoxazole was obtained.

J. Heterocyclic Chem., **50**, 381 (2013).

INTRODUCTION

Furoxan was considered as an excellent structure for constructing high energetic density materials (HEDMs), as it could increase crystal density and improve explosive performance [1–3]. Because of this, the introduction of one or more structures of furoxan to an explosive molecule has been actively researched by a great number of researchers in recent years [4,6]. Some derivatives of furoxan also could be used as high-density explosives. 3,4-Bis(4-aminofurazano-3-yl)furoxan (DATF) was among the most promising HEDM candidates derivated from furoxan for its excellent properties [7, 8].

DATF could be obtained from propanedinitrile according to the reported procedure [9, 10] shown in Scheme 1. Unfortunately, the procedure suffered from low yield of the last step. A clear mechanism of this reaction might provide idea for some scholars to improve the yield as well as understand the microcosmic reactive process more clearly. To our knowledge, only a primitive mechanism was reported, which proposed an intermediate, 3-amino-4-oxycyanofurazan (AOCF) [11, 12], presenting before the formation of DATF (Scheme 2). However, the mechanism was unproved, because AOCF was unstable even at low temperature and could not be isolated from the reaction system [13–18].

Here, we report a method that can prove the existence of AOCF in the reaction by capturing it *in situ* and thereof prove the mechanism.

RESULTS AND DISCUSSION

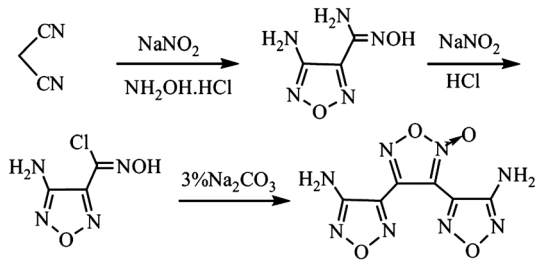
To prove the existence of an unstable intermediate, it was good idea to capture and/or convert it to a stable compound before it decomposed. If the stable compound could be isolated and identified, the existence of the unstable intermediate can be proved.

As to AOCF, alkynes were applied to capture it, because they could form stable isoxazoles through 1,3-dipolar cycloaddition reaction [19, 20], which have been extensively studied experimentally and theoretically (Scheme 3). This reaction was chosen because of its high yield, stereoselection, and mild condition.

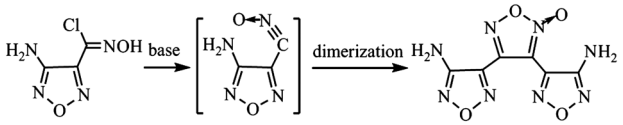
It should be noted that the dimerization of AOCF leading to DATF was a "side reaction" at this moment and must be avoided, so the capturing was carried out under neutral condition. Under this condition, the hydrogen chloride elimination of 3-amino-4-chloroximinofurazan was slow and the concentration of nitrile oxide was low, so the dimerization of nitrile oxide was prohibited. At the same time, because of the electron-withdrawing character of nitrile oxide and high concentration of alkynes, 1,3-dipolar cycloaddition reaction was the dominant reaction, and also all of the nitrile oxide generated *in situ* was converted to isoxazoles.

Hexabutylditin ($Bu_3SnSnBu_3$) was used as initiator, as it works well under this condition. This reaction may be initiated by homolytic cleavage of hexabutylditin and formed tributyltin radical. The radical would deprive the chlorine atom of hydroximic chloride, and AOCF was

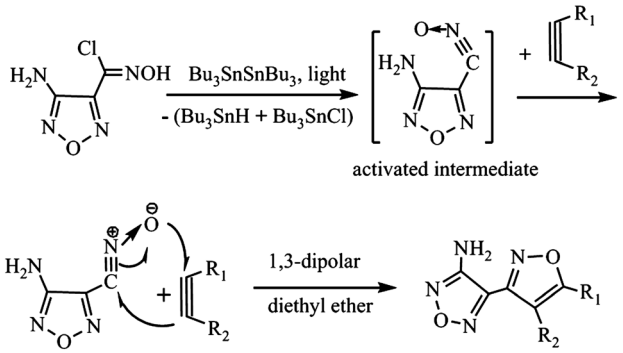
Scheme 1



Scheme 2



Scheme 3



obtained. It should be mentioned that DATF could be isolated from the reaction mixture, if one of the alkynes was absent.

Five alkynes were applied to capture AOCF, and five isoxazoles were obtained with high yield. The structures of the isoxazoles were confirmed by some analytic data. The general synthetic process was shown as follows (Scheme 4).

Single crystals of **4** were cultured by slow evaporation of its ethanol solution. The X-ray single crystal structure of **4** was determined. The nonhydrogen coordinates and thermal parameters were listed in Table 1. The bond lengths were summarized in Table 2. The bond angles were summarized in Table 3. The dihedral angels were summarized in Table 4. The molecular structure and 3D packing of **4** were shown in Figures 1 and 2, respectively.

Scheme 4

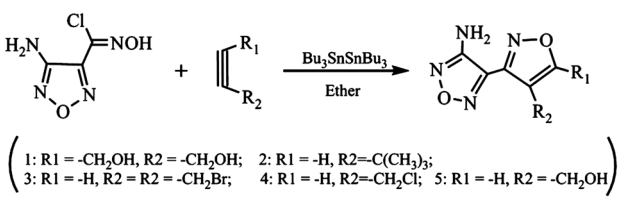


Table 1

Atomic coordinates ($\times 10^4$) and equivalent isotropic displacement parameters ($nm^2 \times 10^3$)$^{\alpha}$.

Atoms	*x*	*y*	*z*	*U*(eq)$^{\alpha}$
Cl(1)	11 (1)	11322 (1)	1067 (1)	63 (1)
N(1)	2459 (1)	10369 (4)	6260 (1)	64 (1)
N(2)	1934 (1)	7137 (4)	6631 (1)	60 (1)
N(3)	1207 (1)	5398 (5)	5122 (1)	69 (1)
N(4)	1755 (1)	10116 (4)	4106 (1)	57 (1)
O(1)	1427 (1)	5245 (4)	6073 (1)	77 (1)
O(2)	1490 (1)	10459 (3)	3120 (1)	60 (1)
C(1)	2013 (1)	8409 (4)	6016 (2)	45 (1)
C(2)	1551 (1)	7286 (5)	5071 (1)	45 (1)
C(3)	1421 (1)	8092 (4)	4143 (1)	44 (1)
C(4)	945 (1)	7036 (5)	3214 (2)	48 (1)
C(5)	1005 (1)	8596 (4)	2611 (2)	47 (1)
C(6)	645 (1)	8760 (5)	1545 (2)	55 (1)

Figure 1 showed the molecular structure of **4**, which was consisted of a chloromethyl group and an amino furazano structure. It could be seen from Tables 2–4 that bond lengths, angles, and dihedral angels of **4** were in the normal range [21]. The chloromethyl group was connected by C5 to the isoxazone ring. Therefore, in the reaction system, the product was unique and had no isomeric compound.

CONCLUSIONS

AOCF, an unstable intermediate for the synthesis of DATF from 3-amino-4-chloroximino furazan was captured *in situ* by alkynes and converted to isoxazoles through 1,3-dipolar cycloaddition reaction. The corresponding isoxazoles were obtained with high yield and purity. In addition, their structures were confirmed by IR, ^{1}H NMR, ^{13}C NMR, MS, elemental analysis, and single crystal X-ray diffraction. These results proved the proposed mechanism.

EXPERIMENTAL

IR spectrum was recorded using a Nicolet Model NEXUS 870 FTIR instrument and a model DTGS detector. KBr pellet samples, well mixed by about 0.7 mg of sample and 150 mg of KBr, were used. The ^{1}H NMR and ^{13}C NMR spectra were performed on a Bruker AV 500 MHz superconducting NMR spectrometer (Bruke Biospin International AG, Switzerland). DMSO-d_6 was the solvent, and tetramethyl silane was an internal standard. Elemental analyses of carbon, hydrogen, and nitrogen were carried out with an Elementary Vario EL-III microanalyzer. Differential scanning calorimetry (DSC) measurements were carried out on the TA instruments, Model DSC 910S under static atmosphere of N_2 at the pressure of 0.1 and 1 MPa with heating rate of 10°C min^{-1}. Samples weighting from 0.5 to 1.0 mg, loaded in an aluminum sample cell, were used. 3-Amino-4-chloroximinofurazan was prepared in our laboratory [7], and other reagents were available commercially.

Table 2

Selected bond lengths (nm × 10^{-1}) for compound **4** crystal structure parameters.

Bonds	Exp	Bonds	Exp	Bond	Exp
Cl(1)—C(6)	1.794 (2)	N(3)—O(1)	1.366 (2)	C(4)—C(5)	1.340 (3)
N(1)—C(1)	1.333 (3)	N(4)—C(3)	1.307 (3)	C(4)—H(4)	0.9300
N(1)—H(1A)	0.8600	N(4)—O(2)	1.402 (2)	C(5)—C(6)	1.480 (3)
N(1)—H(1B)	0.8600	O(2)—C(5)	1.349 (3)	C(6)—H(6A)	0.9700
N(2)—C(1)	1.312 (3)	C(1)—C(2)	1.433 (3)	C(6)—H(6B)	0.9700
N(2)—O(1)	1.398 (3)	C(2)—C(3)	1.456 (3)		
N(3)—C(2)	1.287 (3)	C(3)—C(4)	1.410 (3)		

Table 3

Selected bond angles (in °) for compound **4** crystal structure parameters.

Bond angles	Exp	Bond	Exp	Bond	Exp
C(1)—N(1)—H(1A)	120.0	N(1)—C(1)—C(2)	127.54 (19)	C(4)—C(5)—O(2)	109.94 (18)
C(1)—N(1)—H(1B)	120.0	N(3)—C(2)—C(1)	109.66 (19)	C(4)—C(5)—C(6)	134.2 (2)
H(1A)—N(1)—H(1B)	120.0	N(3)—C(2)—C(3)	120.9 (2)	O(2)—C(5)—C(6)	115.83 (19)
C(1)—N(2)—O(1)	105.10 (18)	C(1)—C(2)—C(3)	129.4 (2)	C(5)—C(6)—Cl(1)	110.35 (16)
C(2)—N(3)—O(1)	106.26 (18)	N(4)—C(3)—C(4)	111.93 (19)	C(5)—C(6)—H(6A)	109.6
C(3)—N(4)—O(2)	105.20 (16)	N(4)—C(3)—C(2)	119.54 (19)	Cl(1)—C(6)—H(6A)	109.6
N(3)—O(1)—N(2)	110.82 (16)	C(4)—C(3)—C(2)	128.5 (2)	C(5)—C(6)—H(6B)	109.6
C(5)—O(2)—N(4)	108.52 (15)	C(5)—C(4)—C(3)	104.4 (2)	Cl(1)—C(6)—H(6B)	109.6
N(2)—C(1)—N(1)	124.3 (2)	C(5)—C(4)—H(4)	127.8	H(6A)—C(6)—H(6B)	108.1
N(2)—C(1)—C(2)	108.2 (2)	C(3)—C(4)—H(4)	127.8		

Table 4

Selected dihedral angles (in deg) for compound **4** crystal structure parameters.

Dihedral angles	Exp	Bond	Exp	Bond	Exp
C(2)—N(3)—O(1)—N(2)	−0.2 (3)	N(2)—C(1)—C(2)—C(3)	176.5 (2)	C(2)—C(3)—C(4)—C(5)	176.2 (2)
C(1)—N(2)—O(1)—N(3)	0.2 (3)	N(1)—C(1)—C(2)—C(3)	−4.5 (4)	C(3)—C(4)—C(5)—O(2)	1.1 (2)
C(3)—N(4)—O(2)—C(5)	0.0 (2)	O(2)—N(4)—C(3)—C(4)	0.7 (3)	C(3)—C(4)—C(5)—C(6)	−176.0 (2)
O(1)—N(2)—C(1)—N(1)	−179.1 (2)	O(2)—N(4)—C(3)—C(2)	−176.88 (19)	N(4)—O(2)—C(5)—C(4)	−0.7 (2)
O(1)—N(2)—C(1)—C(2)	−0.1 (2)	N(3)—C(2)—C(3)—N(4)	176.4 (2)	N(4)—O(2)—C(5)—C(6)	176.96 (19)
O(1)—N(3)—C(2)—C(1)	0.1 (3)	C(1)—C(2)—C(3)—N(4)	0.2 (4)	C(4)—C(5)—C(6)—Cl(1)	93.4 (3)
O(1)—N(3)—C(2)—C(3)	−176.8 (2)	N(3)—C(2)—C(3)—C(4)	−0.8 (4)	O(2)—C(5)—C(6)—Cl(1)	−83.6 (2)
N(2)—C(1)—C(2)—N(3)	0.0 (3)	C(1)—C(2)—C(3)—C(4)	−177.0 (2)		
N(1)—C(1)—C(2)—N(3)	179.0 (2)	N(4)—C(3)—C(4)—C(5)	−1.2 (3)		

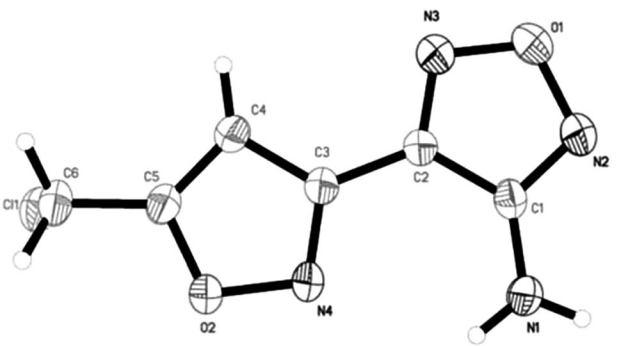


Figure 1. Molecular structure for compound **4**.

General procedure for DATF. To 600-mL diethyl ether solution of 3-amino-4-chloroximinofurazan (48 g, 0.295 mol) in a three-necked, round-bottomed flask fitted with a mechanical stirrer and a dropping funnel, 490-mL 3% aqueous solution of sodium carbonate was added dropwise at 0∼3°C (Scheme 5). After the reaction, the temperature was maintained at 2∼10°C for 3 h [7]. The solution was evaporated to dryness under reduced pressure, and the residue was recrystallized from ethanol and afforded the product 27.5 g with a yield of 73.6%.

^{1}H NMR (DMSO-d_6, 500 MHz) δ, ppm: 6.61(s, 4H, NH_2); ^{13}C NMR (DMSO-d_6, 125 MHz) δ, ppm: 156.4, 155.5, 133.7, 136.6, 104.6, 147.0; IR (KBr) υ: 3459, 3332(NH_2), 1635,1559, 1046, 1414, 1401, 1361 (furazan), 1609, 1533, 1463, 991(furoxan) cm^{-1}; Anal. calcd for $C_6N_8H_4O_4$: C 28.58, H 1.60, N 44.44; Found C 28.63, H 1.31, N 44.46.

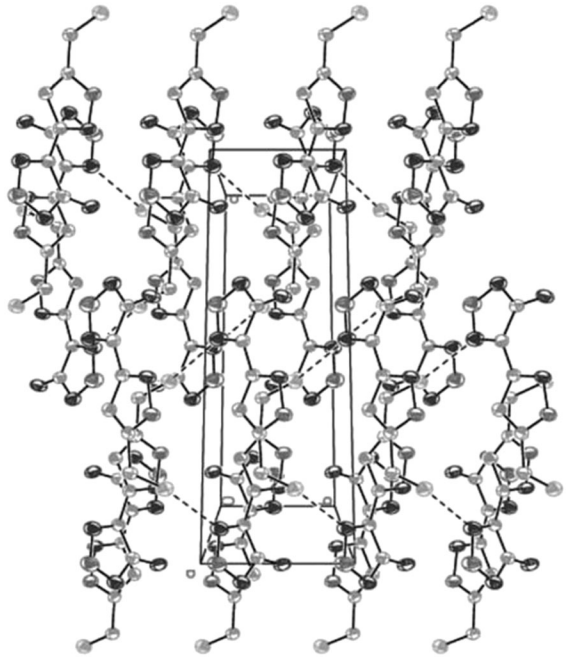
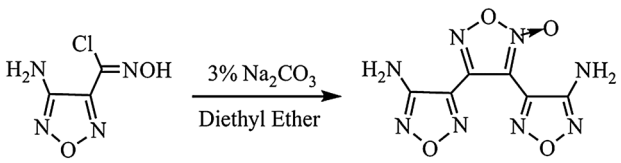


Figure 2. Packing of compound **4** molecules in the crystal.

Scheme 5



General procedure for the five isoxazones. 3-Amino-4-chloroximinofurazan (0.4 g, 2.46 mmol) in 30-mL diethyl ether was transferred into a three-necked, round-bottomed flask fitted with a mechanical stirrer and a dropping funnel. Hexabutylditin (1.4 g, 2.46 mmol) and an alkyne (1.2 mmol) were then added. The reaction mixture was irradiated with a General Electric sunlamp for 12 h. The reaction temperature was maintained at 25° C by keeping the distance between the reaction flask and the sunlamp at about 17 inches [20]. The solvent was evaporated to dryness, and the residue was recrystallized from ethanol to afford the pure product.

3-(4-Aminofurazan-3-yl)-4,5-dihydroxylmethylisoxazone (1). Yield: 0.35 g (67.1%). m.p.143.55°C, T.p. 310.79°C (DSC, 10°C min^{-1}); ^{1}H NMR (DMSO-d_6, 500 MHz) δ, ppm: 6.427(s, 2H, NH_2), 5.675(t, J = 6.0 Hz, 1H, OH), 5.121(t, J = 5.0 Hz, 1H, OH), 4.731(d, J = 6.0 Hz, 2H, CH_2), 4.628 (d, J = 5.0 Hz, 2H, CH_2); ^{13}C NMR (DMSO-d_6, 125 MHz) δ, ppm: 170.644, 155.349, 151.150, 138.518, 115.689, 53.217, 51.862; IR (KBr) υ: 3472, 3349(NH_2), 3291(OH), 2956~2869(CH_2), 1635,1552 (furazan) cm^{-1}; Anal. calcd for $C_7H_8N_4O_4$: C 39.62, H 3.774, N 26.41; found C 39.74, H 3.752, N 26.35; MS (EI) m/z(%): 212 (M^+,18), 176(35), 155(100), 137(60), 109(35),68(50), 53 (85).

3-(4-Aminofurazan-3-yl)-5-tert-butylisoxazone (2). Yield: 0.33 g (64.5%). m.p. 162.82°C (DSC, 10°C min^{-1}); ^{1}H NMR(DMSO-d_6, 500 MHz) δ, ppm: 6.867(s, H, CH), 6.395(s, 2H, NH_2), 1.376 (s, 9H, $3CH_3$); ^{13}C NMR (DMSO-d_6, 125 MHz) δ, ppm: 182.260, 154.941, 151.791, 138.631, 98.198, 32.557, 28.393; IR (KBr) υ: 3464, 3343 (NH_2), 2968~2871(CH_3), 1632,1553 (furazan) cm^{-1}; Anal. calcd for $C_7H_8N_4O_4$: C 51.92, H 5.769, N 26.92; found C 51.74, H 5.802, N 26.83; MS (EI) m/z(%): 208 (M^+, 40), 151(100), 135(80),109(75), 95(45),43(82).

3-(4-Aminofurazan-3-yl)-5-brommethylisoxazone (3). Yield: 0.44 g (73.0%) m.p.147.28°C (DSC, 10°C min^{-1}); ^{1}H NMR (DMSO-d_6, 500 MHz) δ, ppm: 7.197(s, H, CH), 6.431(s, 2H, NH_2), 4.949(s, 2H, CH_2); ^{13}C NMR(DMSO-d_6, 125 MHz) δ, ppm: 169.563, 154.937, 152.370, 138.291, 103.087, 19.056; IR (KBr) υ: 3453, 3325(NH_2), 1634,1558(furazan), 733(Cl) cm^{-1}; Anal. calcd for $C_6H_5N_4O_2Br$: C 29.39, H 2.041, N 22.85; found C 29.54, H 2.235, N 22.81; MS (EI) m/z(%): 244 (M^+,27), 246($(M+2)^+$, 27), 187(38), 165(10), 108(83), 68 (100), 53(39),42(15).

3-(4-Aminofurazan-3-yl)-5-chloromethyl-isoxazone (4). Yield: 0.33 g (66.9%). m.p.122.72°C (DSC, 10°C min^{-1}); ^{1}H NMR (DMSO-d_6, 500 MHz) δ, ppm: 7.203(s, H, CH), 6.434(s, 2H, NH_2), 5.083(s, 2H, CH_2); ^{13}C NMR(DMSO-d_6, 125 MHz) δ, ppm: 169.304, 154.963, 152.301, 138.297, 103.286, 33.844; IR (KBr) υ: 3459,3334(NH_2), 3259~3160(CH_2), 1634,1558(furazan), 734(Cl) cm^{-1}; Anal. calcd for $C_6H_5N_4O_2Cl$: C 35.91, H 2.494, N 27.93; found C 35.98, H 2.556, N 27.69; MS (EI) m/z(%): 200(M^+,46), 202($(M+2)^+$, 15), 143(100), 107(17), 68 (76), 58(45),49(28).

3-(4-Aminofurazan-3-yl)-5-hydroxymethyl-isoxazone (5). Yield: 0.29 g (64.8%). m.p.171.22°C (DSC, 10°C min^{-1}); ^{1}H NMR (DMSO-d_6, 500 MHz) δ, ppm: 6.950(s, H, CH), 6.412(s, 2H, NH_2), 5.826(t, J = 6.0 Hz, 1H, OH), 4.690(d, J = 6.0 Hz, 2H, CH_2); ^{13}C NMR(DMSO-d_6, 125 MHz) δ, ppm:174.673, 155.008, 151.859, 138.592, 100.772, 54.613; IR (KBr) υ: 3472, 3359(NH_2), 3131(OH), 2948~2884 (CH_2), 1633,1558(furazan) cm^{-1}; Anal. calcd for $C_6H_6N_4O_3$: C 39.56, H 3.297, N 30.77; found C 39.76, H 3.450, N 30.47; MS (EI) m/z(%): 182 (M^+, 40), 125(100), 68(75), 53 (28),40(15).

Single crystal X-ray diffraction of 4. The suitable crystal of **4** with dimensions of 0.34 × 0.21 × 0.13 mm^3 was mounted and transferred to a CCD-equipped diffractometer. The X-ray diffraction data were collected using Mo kα (λ = 0.071073 nm) radiation. Cell parameters were determined in the range of $2.44° < \theta < 25.10°$ at the temperature of 296(2) K. A total of 3880 independent reflections (R_{int} = 0.0304) were obtained, among which 1468 observed reflections with $I > 2\sigma(I)$ were used for the determination and refinement of the crystal structure in the range of $-18 \le h \le 29$, $-5 \le k \le 5$, and $-20 \le l \le 20$, respectively. The coordinates of atom were obtained by direct method. The results were optimized by the least-squares method with anisotropic thermal parameters. The empirical formula was $C_6H_5ClN_4O_2$. The molecular weight of compound **4** was 200.59. The crystal of **4** belongs to monoclinic, space group C2/c with a = 2.4812(8) nm, α = 90°, b = 0.48451(16) nm, β = 124.829(3)°, c = 1.6821(6) nm, γ = 90°, V = 1.6599(9) nm^3, Z = 8, D_c = 1.605 g cm^{-3}, μ = 0.431 mm^{-1}, F(000) = 816. The maximum peak and the minimum peak on the Fourier map were 191 and −353 e·nm^{-3}, respectively. The refinement was converged with R_1 =0.0377, ωR_2 =0.0917, of which, $w = 1/[s^2(F_0)^2+(0.0377P)^2+0.0000P]$, $P = (F + 2F)/3$, S =1.072. All calculations were corrected by *Lp*. The crystal structure resolve and correction were processed using SHELX-97 program package [22, 23] on Founder −5166, respectively.

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