Tandem Hetero Diels-Alder Reaction: Synthesis of Oxygenated Macrocycles

Brian R. Bear and Kenneth J. Shea*

Department of Chemistry, 516 Rowland Hall, University of California, Irvine,

Irvine, California 92697-2025

- X-ray crystallographic data for compounds **syn-3** and **anti-3**.

X-ray crystallographic data for compound syn-3

Table 1. Crystal data and structure refinement for **syn-3**.

Identification code	**syn-3**	
Empirical formula	$C_{32}\ H_{36}\ O_8$	
Formula weight	548.61	
Temperature	158 K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	*C*2/*c*	
Unit cell dimensions	a = 22.0121(18) Å	α= 90°.
	b = 5.3654(4) Å	β= 101.084(3)°.
	c = 24.938(2) Å	γ = 90°.
Volume	2890.3(4) Å^3	
Z	4	
Density (calculated)	1.261 Mg/m^3	
Absorption coefficient	0.090 mm^{-1}	
F(000)	1168	
Crystal size	0.23 x 0.12 x 0.11 mm^3	
Theta range for data collection	1.66 to 24.71°.	
Index ranges	$-25 \le h \le 25$, $-6 \le k \le 6$, $-29 \le l \le 29$	
Reflections collected	10419	
Independent reflections	2460 [R(int) = 0.0935]	
Completeness to theta = 24.71°	99.8 %	
Absorption correction	None	
Max. and min. transmission	0.9902 and 0.9796	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	2460 / 0 / 140	
Goodness-of-fit on F^2	1.136	
Final R indices [I > 2sigma(I)]	R1 = 0.1306, wR2 = 0.2853	
R indices (all data)	R1 = 0.2051, wR2 = 0.3268	
Largest diff. peak and hole	0.435 and -0.323 e.Å^{-3}	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **syn-3**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
C(1)	4807(3)	3153(13)	1385(3)	52(2)
C(2)	4574(3)	1899(14)	848(3)	64(2)
C(3)	4050(3)	90(13)	867(3)	62(2)
C(4)	3620(3)	1274(12)	1198(2)	56(2)
C(5)	3759(3)	3288(11)	1507(2)	40(2)
C(6)	3324(3)	4461(12)	1812(2)	42(2)
C(7)	3171(3)	7716(13)	2409(3)	53(2)
C(8)	3585(3)	9249(13)	2830(3)	55(2)
C(9)	3936(3)	7716(14)	3309(3)	63(2)
C(10)	4439(3)	6023(13)	3168(3)	57(2)
C(11)	3775(2)	-772(5)	329(1)	43(3)
C(12)	4111(2)	-2204(7)	23(1)	44(3)
C(13)	3845(2)	-2908(7)	-507(1)	55(3)
C(14)	3244(2)	-2181(8)	-731(1)	60(3)
C(15)	2909(2)	-749(7)	-425(1)	93(5)
C(16)	3174(2)	-45(6)	104(1)	72(4)
O(1)	4312(1)	4499(4)	1558(1)	53(1)
O(2)	2809(1)	3704(6)	1813(1)	67(2)
O(3)	3562(1)	6438(4)	2086(1)	49(1)
O(4)	4750(2)	4880(7)	3671(1)	62(1)
C(11B)	3593(5)	-670(20)	252(4)	77(7)
C(12B)	3555(7)	-3130(20)	70(6)	110(9)
C(13B)	3247(8)	-3687(16)	-457(6)	116(10)
C(14B)	2977(6)	-1790(20)	-802(4)	80(7)
C(15B)	3014(4)	664(18)	-620(3)	31(4)
C(16B)	3323(5)	1222(16)	-93(4)	27(3)

Table 3. Bond lengths [Å] and angles [°] for **syn-3**.

C(1)-O(4)#1	1.372(8)
C(1)-O(1)	1.439(6)
C(1)-C(2)	1.500(9)
C(2)-C(3)	1.515(10)
C(3)-C(11)	1.439(7)
C(3)-C(4)	1.509(9)
C(3)-C(11B)	1.715(11)
C(4)-C(5)	1.328(8)
C(5)-O(1)	1.365(6)
C(5)-C(6)	1.473(8)
C(6)-O(2)	1.204(6)
C(6)-O(3)	1.316(7)
C(7)-O(3)	1.459(6)
C(7)-C(8)	1.496(9)
C(8)-C(9)	1.533(9)
C(9)-C(10)	1.525(9)
C(10)-O(4)	1.446(7)
C(11)-C(12)	1.3900
C(11)-C(16)	1.3900
C(12)-C(13)	1.3900
C(13)-C(14)	1.3900
C(14)-C(15)	1.3900
C(15)-C(16)	1.3900
O(4)-C(1)#1	1.372(7)
C(11B)-C(12B)	1.3900
C(11B)-C(16B)	1.3900
C(12B)-C(13B)	1.3900
C(13B)-C(14B)	1.3900
C(14B)-C(15B)	1.3900
C(15B)-C(16B)	1.3900
O(4)#1-C(1)-O(1)	106.6(5)
O(4)#1-C(1)-C(2)	109.8(5)
O(1)-C(1)-C(2)	110.2(5)

C(1)-C(2)-C(3)	112.9(6)
C(11)-C(3)-C(4)	116.8(6)
C(11)-C(3)-C(2)	111.2(5)
C(4)-C(3)-C(2)	108.0(6)
C(11)-C(3)-C(11B)	11.3(4)
C(4)-C(3)-C(11B)	105.6(7)
C(2)-C(3)-C(11B)	116.3(6)
C(5)-C(4)-C(3)	124.2(6)
C(4)-C(5)-O(1)	122.9(5)
C(4)-C(5)-C(6)	123.2(6)
O(1)-C(5)-C(6)	113.9(5)
O(2)-C(6)-O(3)	123.5(5)
O(2)-C(6)-C(5)	124.2(6)
O(3)-C(6)-C(5)	112.3(5)
O(3)-C(7)-C(8)	107.5(4)
C(7)-C(8)-C(9)	113.6(6)
C(10)-C(9)-C(8)	114.7(5)
O(4)-C(10)-C(9)	107.2(5)
C(12)-C(11)-C(16)	120.0
C(12)-C(11)-C(3)	121.1(3)
C(16)-C(11)-C(3)	118.8(3)
C(13)-C(12)-C(11)	120.0
C(12)-C(13)-C(14)	120.0
C(15)-C(14)-C(13)	120.0
C(14)-C(15)-C(16)	120.0
C(15)-C(16)-C(11)	120.0
C(5)-O(1)-C(1)	116.5(4)
C(6)-O(3)-C(7)	116.6(4)
C(1)#1-O(4)-C(10)	115.2(4)
C(12B)-C(11B)-C(16B)	120.0
C(12B)-C(11B)-C(3)	120.4(8)
C(16B)-C(11B)-C(3)	119.1(8)
C(11B)-C(12B)-C(13B)	120.0
C(12B)-C(13B)-C(14B)	120.0
C(15B)-C(14B)-C(13B)	120.0
C(16B)-C(15B)-C(14B)	120.0

C(15B)-C(16B)-C(11B) 120.0

Symmetry transformations used to generate equivalent atoms:
#1 -x+1,y,-z+1/2

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **syn-3**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
C(1)	49(4)	56(4)	53(4)	-1(3)	15(3)	21(4)
C(2)	66(5)	60(5)	69(5)	0(4)	24(4)	20(4)
C(3)	91(6)	47(4)	48(4)	2(3)	16(4)	13(4)
C(4)	74(5)	55(4)	39(4)	6(3)	15(3)	-9(4)
C(5)	42(4)	34(3)	45(3)	12(3)	10(3)	0(3)
C(6)	33(3)	51(4)	42(3)	15(3)	9(3)	2(3)
C(7)	30(3)	53(4)	76(5)	-16(4)	15(3)	3(3)
C(8)	43(4)	53(4)	72(5)	-14(4)	17(3)	-1(3)
C(9)	49(4)	72(5)	72(5)	-21(4)	23(4)	-16(4)
C(10)	46(4)	63(4)	58(4)	-3(4)	1(3)	-17(4)
O(1)	42(3)	46(3)	72(3)	-4(2)	15(2)	8(2)
O(2)	49(3)	94(4)	63(3)	-24(3)	26(2)	-28(3)
O(3)	32(2)	42(2)	74(3)	-12(2)	16(2)	-1(2)
O(4)	40(3)	80(4)	67(3)	-9(3)	13(2)	-13(3)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for **syn-3**.

	x	y	z	U(eq)
H(1)	4983	1888	1667	62
H(2A)	4920	988	735	77
H(2B)	4429	3186	568	77
H(3A)	4237	-1399	1077	74
H(4A)	3226	531	1184	67
H(7A)	2940	6488	2589	63
H(7B)	2868	8799	2172	63
H(8A)	3332	10522	2973	66
H(8B)	3888	10134	2653	66
H(9A)	4129	8875	3602	75
H(9B)	3635	6678	3457	75
H(10A)	4253	4728	2904	68
H(10B)	4736	7005	3002	68
H(12)	4522	-2701	176	53
H(13)	4075	-3886	-715	66
H(14)	3063	-2662	-1093	72
H(15)	2498	-252	-579	111
H(16)	2945	933	313	86
H(12B)	3739	-4425	306	132
H(13B)	3221	-5364	-581	139
H(14B)	2766	-2172	-1162	96
H(15B)	2830	1960	-856	37
H(16B)	3348	2900	31	32

X-ray crystallographic data for compound anti-3

Table 1. Crystal data and structure refinement for **anti-3**.

Identification code	**anti-3**	
Empirical formula	$C_{32}\ H_{36}\ O_8$	
Formula weight	548.61	
Temperature	163(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	*Pbca*	
Unit cell dimensions	a = 9.1207(6) Å	α= 90°.
	b = 7.8183(5) Å	β= 90°.
	c = 38.380(2) Å	γ = 90°.
Volume	2736.8(3) $Å^3$	
Z	4	
Density (calculated)	1.331 Mg/m^3	
Absorption coefficient	0.095 mm^{-1}	
F(000)	1168	
Crystal size	0.30 x 0.25 x 0.13 mm^3	
Theta range for data collection	1.06 to 28.27°.	
Index ranges	$-11 \le h \le 11$, $-10 \le k \le 10$, $-51 \le l \le 49$	
Reflections collected	26972	
Independent reflections	3357 [R(int) = 0.0351]	
Completeness to theta = 28.27°	98.9 %	
Absorption correction	None	
Max. and min. transmission	0.9877 and 0.9720	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	3357 / 0 / 254	
Goodness-of-fit on F^2	1.121	
Final R indices [I > 2sigma(I)]	R1 = 0.0380, wR2 = 0.0966	
R indices (all data)	R1 = 0.0493, wR2 = 0.1126	
Extinction coefficient	0.0065(9)	
Largest diff. peak and hole	0.403 and -0.207 $e.Å^{-3}$	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **anti-3**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
O(1)	4347(1)	-876(1)	4162(1)	21(1)
O(2)	5651(1)	2642(1)	3680(1)	29(1)
O(3)	6009(1)	1763(1)	4233(1)	20(1)
O(4)	6334(1)	3344(1)	5570(1)	20(1)
C(1)	3498(1)	-2442(2)	4121(1)	18(1)
C(2)	4055(1)	-3481(2)	3819(1)	19(1)
C(3)	3905(1)	-2473(2)	3477(1)	18(1)
C(4)	4515(1)	-704(2)	3538(1)	19(1)
C(5)	4719(1)	-77(1)	3856(1)	18(1)
C(6)	5485(1)	1600(1)	3907(1)	18(1)
C(7)	6896(1)	3288(2)	4295(1)	21(1)
C(8)	7639(1)	3071(2)	4643(1)	19(1)
C(9)	6573(1)	3120(2)	4949(1)	20(1)
C(10)	7329(1)	2851(2)	5296(1)	20(1)
C(11)	4664(1)	-3450(2)	3187(1)	19(1)
C(12)	3865(1)	-4589(2)	2981(1)	23(1)
C(13)	4565(2)	-5623(2)	2739(1)	27(1)
C(14)	6071(2)	-5515(2)	2694(1)	26(1)
C(15)	6876(2)	-4367(2)	2894(1)	26(1)
C(16)	6181(1)	-3346(2)	3140(1)	22(1)

Table 3. Bond lengths [Å] and angles [°] for **anti-3**.

O(1)-C(5)	1.3735(14)
O(1)-C(1)	1.4566(14)
O(2)-C(6)	1.2041(15)
O(3)-C(6)	1.3429(14)
O(3)-C(7)	1.4605(14)
O(4)-C(1)#1	1.3879(14)
O(4)-C(10)	1.4417(14)
C(1)-O(4)#1	1.3879(14)
C(1)-C(2)	1.5056(16)
C(2)-C(3)	1.5370(16)
C(3)-C(4)	1.5088(16)
C(3)-C(11)	1.5171(16)
C(4)-C(5)	1.3294(17)
C(5)-C(6)	1.4981(16)
C(7)-C(8)	1.5088(17)
C(8)-C(9)	1.5256(16)
C(9)-C(10)	1.5131(16)
C(11)-C(12)	1.3945(17)
C(11)-C(16)	1.3974(17)
C(12)-C(13)	1.3892(18)
C(13)-C(14)	1.3867(19)
C(14)-C(15)	1.3911(19)
C(15)-C(16)	1.3895(18)

C(5)-O(1)-C(1)	114.96(9)
C(6)-O(3)-C(7)	115.23(9)
C(1)#1-O(4)-C(10)	114.67(9)
O(4)#1-C(1)-O(1)	106.08(9)
O(4)#1-C(1)-C(2)	110.30(10)
O(1)-C(1)-C(2)	110.90(9)
C(1)-C(2)-C(3)	110.61(10)
C(4)-C(3)-C(11)	114.00(10)
C(4)-C(3)-C(2)	107.75(9)
C(11)-C(3)-C(2)	109.16(10)
C(5)-C(4)-C(3)	122.14(11)
C(4)-C(5)-O(1)	125.70(11)
C(4)-C(5)-C(6)	120.62(11)
O(1)-C(5)-C(6)	113.60(10)
O(2)-C(6)-O(3)	124.43(11)
O(2)-C(6)-C(5)	123.69(11)
O(3)-C(6)-C(5)	111.83(10)
O(3)-C(7)-C(8)	107.53(9)
C(7)-C(8)-C(9)	113.19(10)
C(10)-C(9)-C(8)	112.53(10)
O(4)-C(10)-C(9)	108.49(9)
C(12)-C(11)-C(16)	118.78(11)
C(12)-C(11)-C(3)	119.86(11)
C(16)-C(11)-C(3)	121.11(10)
C(13)-C(12)-C(11)	120.73(12)
C(14)-C(13)-C(12)	120.16(12)
C(13)-C(14)-C(15)	119.63(12)
C(16)-C(15)-C(14)	120.28(12)
C(15)-C(16)-C(11)	120.42(12)

Symmetry transformations used to generate equivalent atoms:

#1 -x+1,-y,-z+1

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **anti-3**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
O(1)	25(1)	21(1)	16(1)	0(1)	2(1)	-5(1)
O(2)	43(1)	21(1)	22(1)	4(1)	-4(1)	-6(1)
O(3)	25(1)	18(1)	17(1)	1(1)	-2(1)	-5(1)
O(4)	22(1)	21(1)	17(1)	3(1)	4(1)	3(1)
C(1)	18(1)	18(1)	18(1)	1(1)	0(1)	-2(1)
C(2)	22(1)	18(1)	18(1)	0(1)	0(1)	-2(1)
C(3)	19(1)	20(1)	17(1)	0(1)	-2(1)	-1(1)
C(4)	20(1)	19(1)	18(1)	2(1)	0(1)	1(1)
C(5)	16(1)	18(1)	19(1)	2(1)	0(1)	1(1)
C(6)	20(1)	17(1)	18(1)	-1(1)	1(1)	3(1)
C(7)	24(1)	18(1)	19(1)	1(1)	0(1)	-6(1)
C(8)	19(1)	18(1)	20(1)	-1(1)	1(1)	-2(1)
C(9)	18(1)	24(1)	19(1)	-1(1)	2(1)	-1(1)
C(10)	20(1)	21(1)	19(1)	1(1)	4(1)	3(1)
C(11)	23(1)	19(1)	16(1)	1(1)	-1(1)	0(1)
C(12)	22(1)	27(1)	21(1)	-2(1)	-2(1)	-2(1)
C(13)	30(1)	27(1)	24(1)	-5(1)	-5(1)	-1(1)
C(14)	31(1)	26(1)	21(1)	-2(1)	3(1)	4(1)
C(15)	23(1)	28(1)	27(1)	0(1)	2(1)	1(1)
C(16)	23(1)	23(1)	21(1)	-1(1)	-2(1)	-2(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for **anti-3**.

	x	y	z	U(eq)
H(1)	2482(15)	-2074(17)	4089(3)	13(3)
H(2A)	5087(18)	-3780(20)	3857(4)	25(4)
H(2B)	3499(17)	-4580(20)	3803(4)	26(4)
H(3)	2840(15)	-2361(17)	3411(3)	17(3)
H(4)	4809(16)	-20(20)	3345(4)	26(4)
H(7A)	7599(17)	3373(19)	4098(4)	27(4)
H(7B)	6239(15)	4262(19)	4294(4)	19(3)
H(8A)	8340(17)	3970(20)	4664(4)	28(4)
H(8B)	8210(15)	2026(19)	4643(4)	19(3)
H(9A)	6078(17)	4260(20)	4955(4)	26(4)
H(9B)	5802(18)	2240(20)	4915(4)	30(4)
H(10A)	7646(16)	1679(19)	5326(4)	23(4)
H(10B)	8226(16)	3588(19)	5317(4)	21(3)
H(12)	2804(18)	-4670(20)	3011(4)	34(4)
H(13)	4009(18)	-6430(20)	2599(4)	32(4)
H(14)	6543(18)	-6250(20)	2527(4)	30(4)
H(15)	7947(19)	-4260(20)	2858(4)	36(4)
H(16)	6739(16)	-2570(20)	3276(4)	24(4)