Enantiopure and quasiracemic crystals of 7-substituted tryptophan derivatives: modulation of the molecular arrangement for functionalized crystals

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1. Crystal structure analysis

1-1. Photographic images of crystals

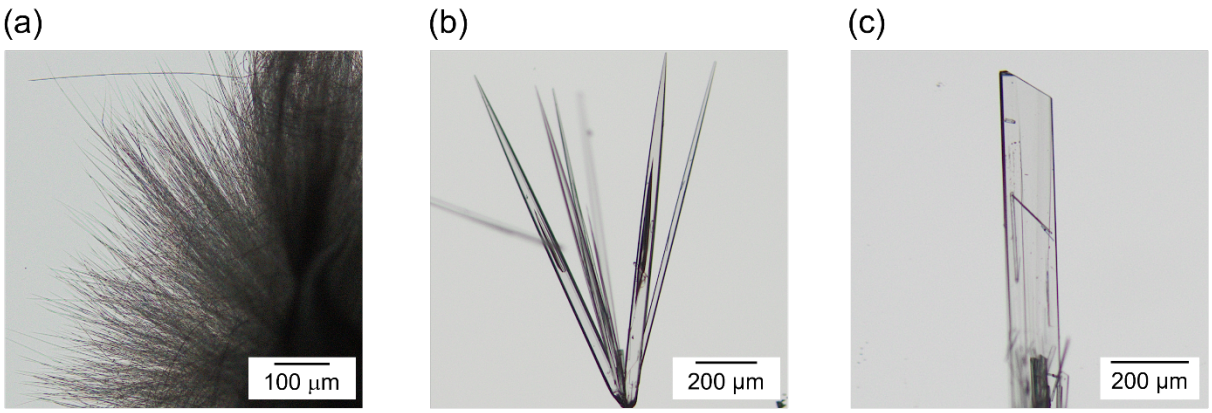

Fig. S1 Photographic images of (a) L-**2**, (b) L-**3**-**α**, and (c) L-**3**-**β**.

1-2. Crystal structure of L-tryptophan (**1**)

Table S1 Crystal data of L-**1**

Crystal	L-**1**-**α**	L-**1**-**β**	L-**1**-**α′**
CCDC	997182[1]	1937607[2]	2266484[3]
Empirical formula	$C_{11}H_{12}N_2O_2$	$C_{11}H_{12}N_2O_2$	$C_{11}H_{12}N_2O_2$
Formula weight	204.23	204.23	204.23
Temperature [K]	123(2)	294	123(1)
Wavelength [Å]	0.71073	0.71073	0.56083
Crystal system	Triclinic	Monoclinic	Triclinic
Space group	*P*1	$P2_1$	*P*1
a [Å]	11.430(3)	9.60851(28)	18.315(2)
b [Å]	11.464(4)	5.20198(14)	5.7707(6)
c [Å]	35.606(9)	19.7511(6)	9.9414(12)
α [°]	84.421(4)	90.0	89.015(9)
β [°]	87.694(4)	93.9514(33)	104.269(10)
γ [°]	60.102(2)	90.0	95.528(9)
V [Å^3]	4025.6(19)	984.88(6)	1013.5(2)
Z	16	4	4
Z’	16	2	4
D_{calcd} [g cm^{-3}]	1.348	1.377	1.338
μ [mm^{-1}]	0.095	0.097	0.059
F(000)	1728	432.0	432
Crystal size [mm^{-1}]	0.62 × 0.28 × 0.14		0.295 × 0.246 × 0.047
Radiation	MoKα	CuKα_1	AgKα
Index ranges	–16<=*h*<=16		–22<=*h*<=22
	–16<=*k*<=16		–6<=*k*<=7
	–51<=*l*<=51		–12<=*l*<=12
Reflections collected	66471		21786
Independent reflections	24736		6702
	R_{int} = 0.0434		R_{int} = 0.1545
Data / restraints / parameters	24736 / 3 / 2178		6702 / 3 / 546
Goodness-of-fit on F^2	1.132		0.632
Final *R* indices	R_1 = 0.0847		R_1 = 0.0456
[*I*>2sigma(*I*)]	wR_2 = 0.2481		wR_2 = 0.0763
R indices (all data)	R_1 = 0.0966		R_1 = 0.1282
	wR_2 = 0.2548		wR_2 = 0.0918
R_{wp}		0.0082	
R_p		0.0061	
Largest diff. peak and hole [eÅ^{-3}]	0.532 and –0.469		0.172 and –0.201

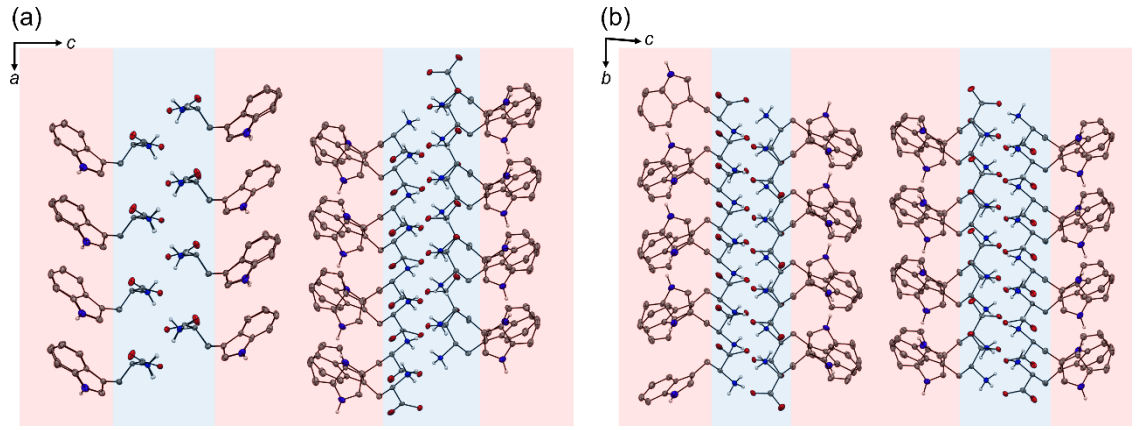

Fig. S2 Single-crystal X-ray structures of L-**1-α** (CCDC: 997182) (C = gray, N = blue, O = red; cyan shading = hydrophilic region, pink shading = hydrophobic region). Packing structures viewed along the (a) *b*-axis and (b) *a*-axis.

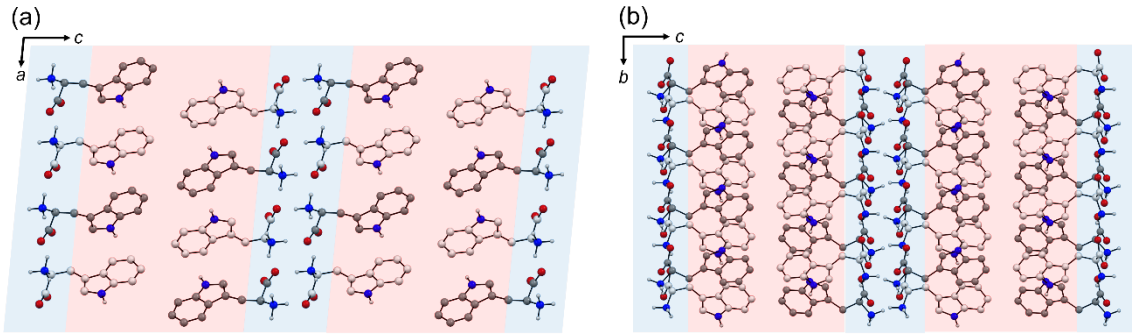

Fig. S3 Single-crystal X-ray structures of L-**1-β** (CCDC: 1937607). The crystal consisted of two crystallographically independent molecules (C = gray or white, N = blue, O = red; cyan shading = hydrophilic region, pink shading = hydrophobic region). Packing structures viewed along the (a) *b*-axis and (b) *a*-axis.

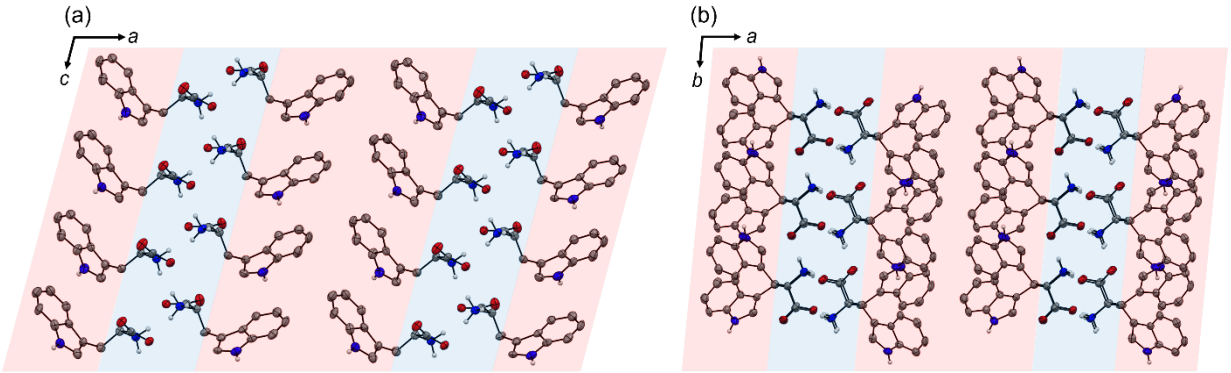

Fig. S4 Single-crystal X-ray structures of L-**1-α′** (CCDC: 2266484) (C = gray, N = blue, O = red; cyan shading = hydrophilic region, pink shading = hydrophobic region). Packing structures viewed along the (a) *b*-axis and (b) *c*-axis.

1-3. Crystal structure of 7-substituted tryptophan L-**2** and L-**3**

Table S2 Crystal data of L-**2** and L-**3**

Crystal	L-**2**	L-**3-α**	L-**3-β**
CCDC	2419033	2419168	2419169
Empirical formula	$C_{12}H_{11}N_3O_2$	$C_{10}H_{11}N_3O_2$	$C_{10}H_{11}N_3O_2$
Formula weight	229.24	205.22	205.22
Temperature [K]	296.15	223	223
Wavelength [Å]	0.0251	1.54184	1.54184
Crystal system	Monoclinic	Tetragonal	Monoclinic
Space group	$P2_1$	$I4$	$P2_1$
a [Å]	11.81(12)	18.69560(8)	9.02963(16)
b [Å]	4.94(8)	18.69560(8)	5.82382(10)
c [Å]	17.74(13)	5.95062(4)	9.72260(17)
α [°]	90	90	90.0000
β [°]	95.86(17)	90	112.326(2)
γ [°]	90	90	90.0000
V [Å^3]	1030(21)	2079.89(2)	472.955(16)
Z	4	8	2
Z'	2	1	1
D_{calcd} [g cm^{-3}]	1.479	1.311	1.441
μ [mm^{-1}]	0.000	0.782	0.861
F(000)	186	864	216.0
Crystal size [mm^{-1}]	0.001 × 0.001 × 0.001	0.6 × 0.1 × 0.05	0.400 × 0.200 × 0.015
Radiation	TEM	CuKα	CuKα
Index ranges	–15<=h<=14	–16<=h<=22	–10<=h<=10
	–6<=k<=6	–17<=k<=22	–6<=k<=6
	–22<=l<=21	–6<=l<=7	–11<=l<=11
Reflections collected	6125	6721	4931
Independent reflections	3407	1974	1695
	R_{int} = 0.1247	R_{int} = 0.0206	R_{int} = 0.1355
Data / restraints / parameters	3407 / 259 / 301	1974 / 1 / 137	1695 / 1 / 152
Goodness-of-fit on F^2	1.185	1.089	1.031
Final R indices	R_1 = 0.1854	R_1 = 0.0238	R_1 = 0.0717
[I>2sigma(I)]	wR_2 = 0.4603	wR_2 = 0.0618	wR_2 = 0.1823
R indices (all data)	R_1 = 0.2544	R_1 = 0.0240	R_1 = 0.0726
	wR_2 = 0.5176	wR_2 = 0.0619	wR_2 = 0.1837
Largest diff. peak and hole [eÅ^{-3}]	0.138 and –0.120	0.119 and –0.168	0.30 and –0.44

Table S3. Hydrogen bonds parameters for L-**2**

D–H···*A*	*D*–H [Å]	H···*A* [Å]	*D*···*A* [Å]	*D*–H···*A* [°]
a (N2B–H4B···O1B)	0.86	1.87	2.69(5)	158
b (N1B–H1B···O1A)	0.89	1.80	2.68(5)	171
c (N1B–H2B···O2A)	0.89	1.85	2.72(4)	165
d (N1B–H3B···O2B)	0.89	1.95	2.74(4)	148
e (N1A–H1A···O1B)	0.89	2.01	2.69(4)	133
f (N1A–H1A···O2B)	0.89	2.33	3.00(5)	132
g (N1A–H2A···N3B)	0.89	2.07	2.94(4)	167
h (N1A–H3A···O2A)	0.89	1.89	2.78(4)	176
i (N2A–H4A···N3A)	0.86	1.98	2.78(5)	153

Table S4. Graph-set analysis for L-**2**[a]

Type of H-bond	a	b	c	d	e	f	g	h	i
a	$C_1^1(8)$								
b	$D_3^3(15)$ <b>a>b	$D_1^1(2)$							
c	$D_3^3(15)$ <c>a>c	$C_2^2(6)$ >b<c	$D_1^1(2)$						
d	$C_2^2(11)$ >a>d	$D_3^3(10)$ <b>d>b	$D_3^3(10)$ <c>d>c	$C_1^1(5)$					
e	$D_3^2(11)$ >e>a<e	$R_2^2(10)$ >b>e	$C_2^2(10)$ >c>e	$D_3^3(10)$ >e>d<e	$D_1^1(2)$				
f	$D_3^3(13)$ >f>a<f	$C_2^2(10)$ >b>f'	$C_2^2(10)$ >c>f	$D_3^3(8)$ >f>d<f	$C_1^2(4)$ >e<f	$D_1^1(2)$			
g	$D_3^3(18)$ >g>a<g	$C_2^2(15)$ >b>g'	$C_2^2(15)$ >c>g	$D_3^3(22)$ >g>d<g	$C_2^2(13)$ >e<g	$C_2^2(13)$ >f<g	$D_1^1(2)$		
h	-	$D_3^3(10)$ >b>h<b	-	$D_3^2(8)$ >c>g<c	$D_3^3(10)$ <e>h>e	$D_3^3(10)$ <f>h>f	$D_3^3(10)$ <g>h>g	$C_1^1(5)$	
i	-	$D_3^3(20)$ >b>i<b	-	$D_3^3(10)$ <c>g'>c	$D_3^3(20)$ <e>i>e	$D_3^3(20)$ <f>i>f	$D_3^3(20)$ <g>i>g	$C_2^2(18)$ >h<i	$C_1^1(6)$

[a] Analyzed by Mercury.[4]

Table S5. Hydrogen bonds parameters for L-**3-α**

D–H···*A*	*D*–H [Å]	H···*A* [Å]	*D*···*A* [Å]	*D*–H···*A* [°]
a (N2–H4···O1)	0.870	2.024	2.862(2)	161.15
b (N1–H2···O2)	0.900	2.068	2.947(2)	165.53
c (N1–H1···N3)	0.900	2.182	3.020(2)	154.68
d (N1–H3···O2)	0.900	1.879	2.777(2)	174.35

Table S6. Graph-set analysis for L-**3-α**[a]

Type of H-bond	a	b	c	d
a	$C_1^1(8)$			
b	$C_2^2(13)$ >a>b	$C_1^1(5)$		
c	$R_2^2(16)$ >a<c	$C_2^2(13)$ >b>c	$C_1^1(8)$	
d	$C_2^2(13)$ >a>d	$C_2^2(10)$ >b>d	$C_2^2(13)$ >c>d	$C_1^1(5)$

[a] Analyzed by Mercury.[4]

Table S7. Hydrogen bonds parameters for L-**3-β**

D–H···*A*	*D*–H [Å]	H···*A* [Å]	*D*···*A* [Å]	*D*–H···*A* [°]
a (N2–H4···O1)	0.95(5)	1.86(6)	2.793(4)	168
b (N1–H1···N3)	0.94(6)	2.31(6)	3.129(5)	146
c (N1–H2···O2)	0.97(7)	1.81(7)	2.775(5)	174
d (N1–H3···O1)	1.00(8)	1.78(8)	2.762(5)	164

Table S8. Graph-set analysis for L-**3-β**[a]

Type of H-bond	a	b	c	d
a	$C_1^1(8)$			
b	$R_2^2(16)$ >a<b	$C_1^1(8)$		
c	$C_2^2(13)$ >a>c	$C_2^2(13)$ >b>c	$C_1^1(5)$	
d	$C_2^2(13)$ >a>d	$C_2^2(13)$ >b>d	$C_2^2(10)$ >c>d	$C_1^1(5)$

[a] Analyzed by Mercury.[4]

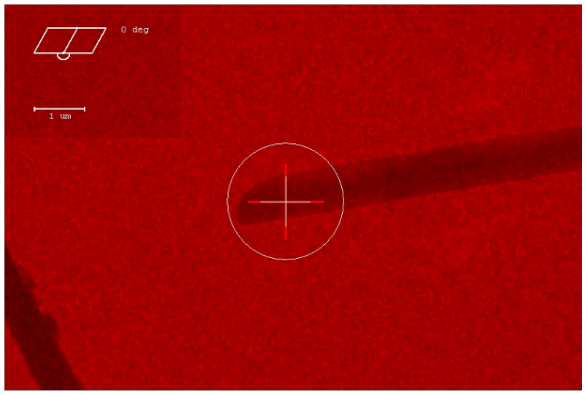

Fig. S5 Electron microscope image of the crystal L-**2**.

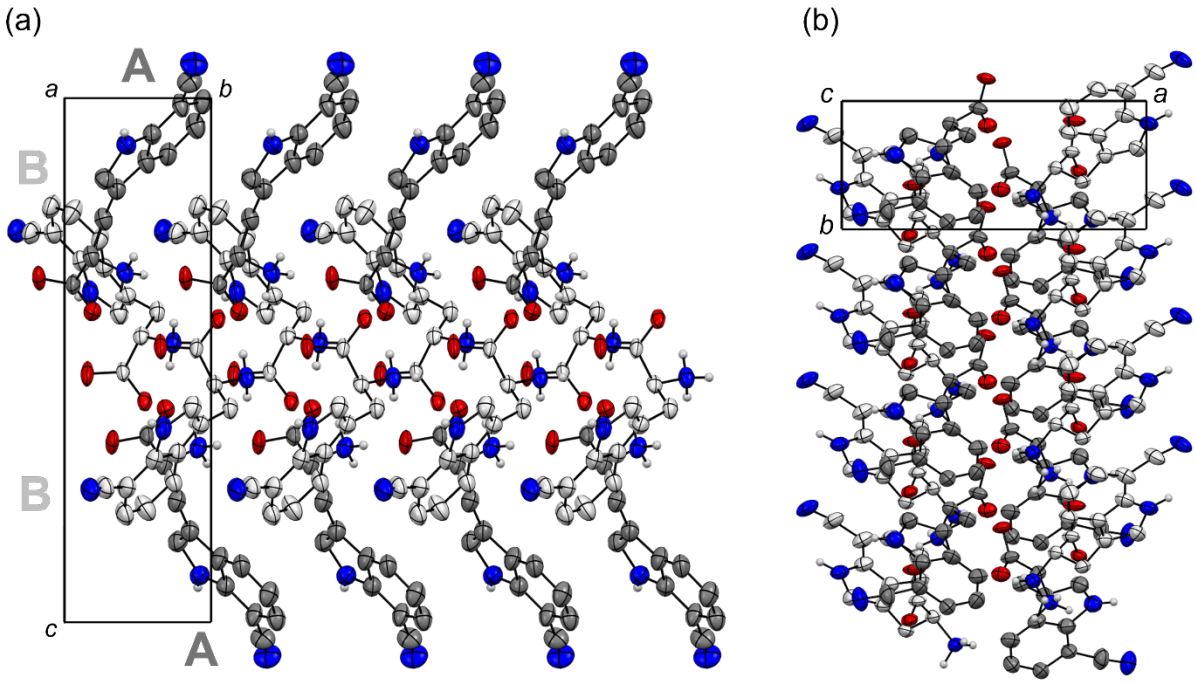

Fig. S6 Molecular arrangement of L-**2** viewed along the (a) *a*-axis and (b) *c*-axis [C = gray (molecule A) and white (molecule B), N = blue, O = red].

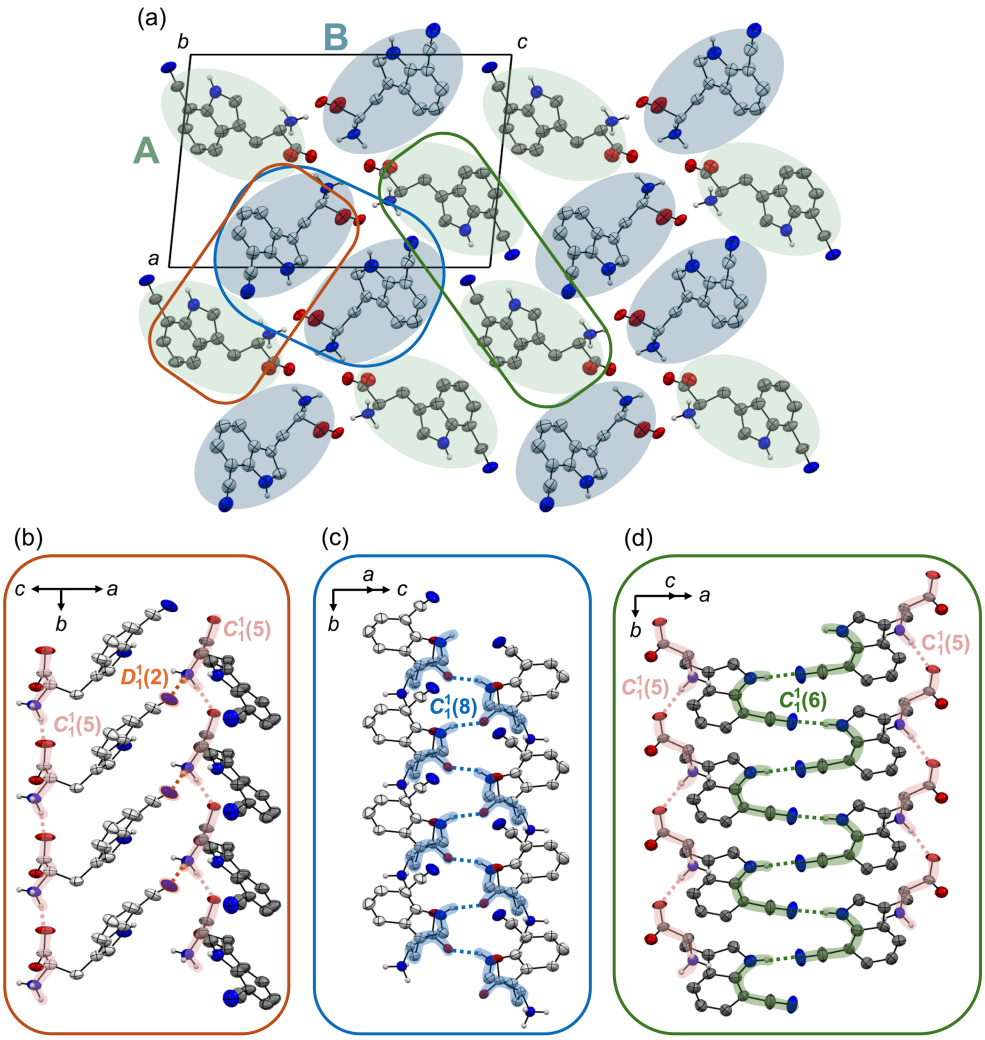

Fig. S7 (a) Packing structure of L-**2** viewed along the *b*-axis, and intermolecular hydrogen bonds formed along the *b*-axis between (b) molecules A and B (CN ⋯ H_3N^+), (c) molecules B and B (COO^- ⋯ HN), and (d) molecules A and A (CN ⋯ HN) [C = gray (molecule A), C = white (molecule B), N = blue, O = red].

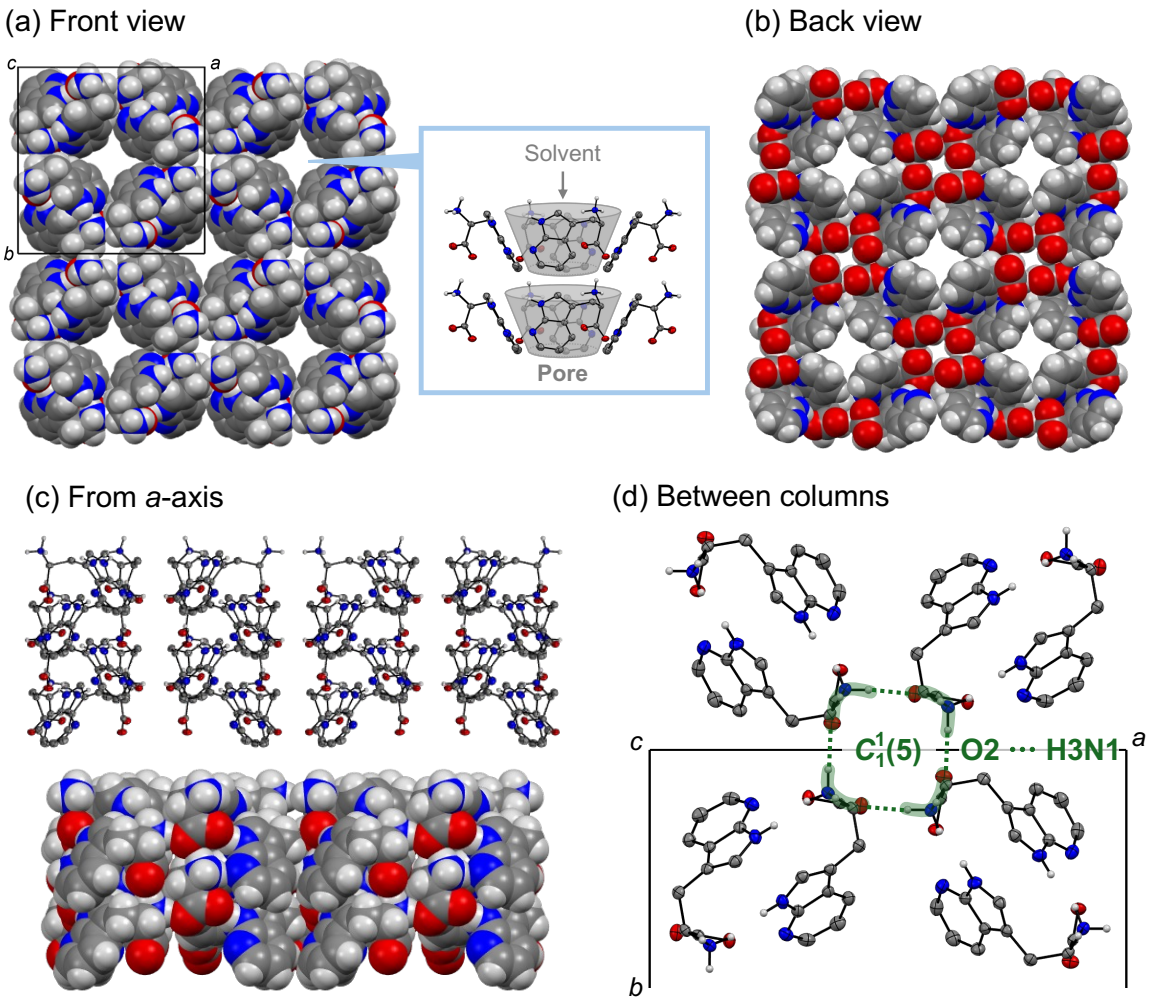

Fig. S8 Packing structures of L-**3-α** (C = gray, N = blue, O = red). (a) Front view and (b) back view of the *ab*-plane. (c) Viewed along the *a*-axis. (d) Hydrogen bonds between columns.

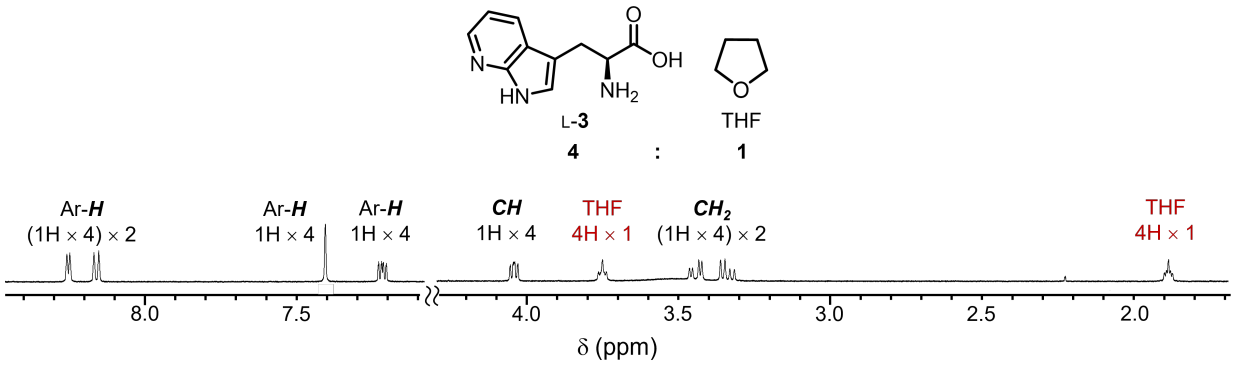

Fig. S9 ^{1}H NMR spectrum (500 MHz, in D_2O) of L-**3-α** that consists of L-**3** and THF.

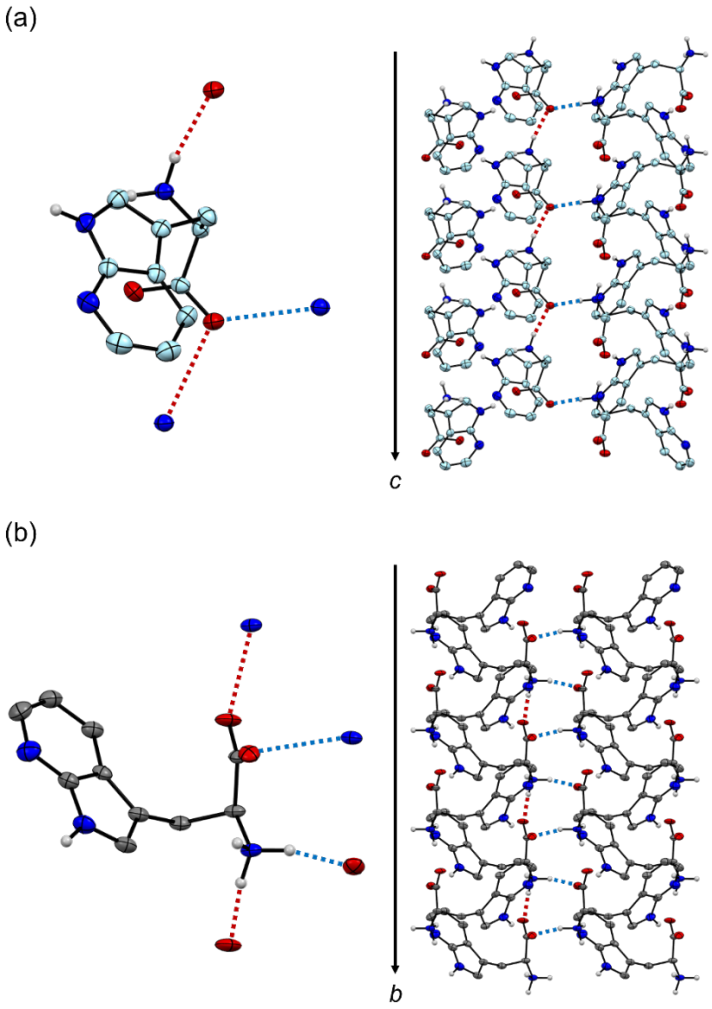

Fig. S10 Column structures of (a) L-**3**-**α** along the *c*-axis and (b) L-**3**-**β** along the *b*-axis [C = light blue (L-**3**-**α**) and gray (L-**3**-**β**), N = blue, O = red]. Red dotted lines indicate hydrogen bonds formed along the column extension direction, while blue dotted lines indicate hydrogen bonds connecting adjacent columns.

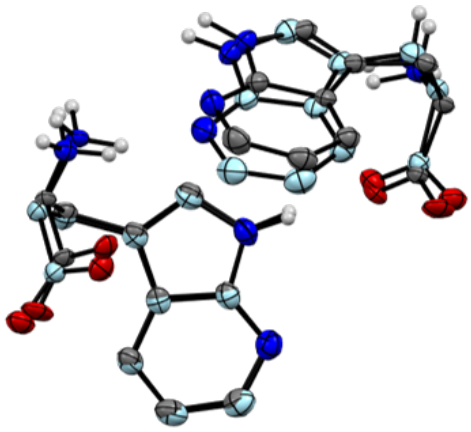

Fig. S11 Comparison of molecular conformation for dimeric L-**3** in α-crystal and β-crystal [C = light blue (L-**3**-**α**) and gray (L-**3**-**β**), N = blue, O = red].

1-4. Crystal structure of racemic crystal DL-**1** and quasiracemic crystal L-**2**/D-**1**

Table S9 Crystal data for DL-**1** and L-**2**/D-**1**

Crystal	DL-**1**[5]	L-**2**/D-**1**
CCDC	997182	2419170
Empirical formula	$C_{11}H_{12}N_2O_2$	$C_{12}H_{11}N_3O_2$ / $C_{11}H_{12}N_2O_2$
Formula weight	204.23	433.46
Temperature [K]	143.15	223(2)
Wavelength [Å]	0.71075	1.54184
Crystal system	Monoclinic	Monoclinic
Space group	$P2_1/c$	$P2_1$
a [Å]	18.981(4)	9.43660(10)
b [Å]	5.7815(12)	5.76640(10)
c [Å]	9.3478(19)	19.6310(3)
α [°]	90	90
β [°]	101.695(7)	101.2100(10)
γ [°]	90	90
V [Å^3]	1004.5(4)	1047.84(3)
Z	4	2
Z'	1	1
D_{calcd} [g cm^{-3}]	1.350	1.374
μ [mm^{-1}]	0.095	0.795
F(000)	432	456
Crystal size [mm^{-1}]	0.23 × 0.1 × 0.04	0.5 × 0.2 × 0.2
Radiation	MoKα	CuKα
Index ranges	–15<=*h*<=24	–11<=*h*<=11
	–7<=*k*<=7	–6<=*k*<=6
	–12<=*l*<=9	–24<=*l*<=24
Reflections collected	7205	16079
Independent reflections	2271	4013
	R_{int} = 0.0741	R_{int} = 0.0374
Data / restraints / parameters	2271 / 0 / 137	4013 / 1 / 313
Goodness-of-fit on F^2	1.068	1.060
Final *R* indices [*I*>2sigma(*I*)]	R_1 = 0.0636	R_1 = 0.0349
	wR_2 = 0.1646	wR_2 = 0.0887
R indices (all data)	R_1 = 0.0871	R_1 = 0.0404
	wR_2 = 0.1804	wR_2 = 0.0922
Largest diff. peak and hole [eÅ^{-3}]	0.385 and –0.255	0.137 and –0.157

Table S10. Hydrogen bonds parameters for L-**2**/D-**1**

D–H···*A*	*D*–H [Å]	H···*A* [Å]	*D*···*A* [Å]	*D*–H···*A* [°]
a (N1L–H2L···O1L)	0.95(3)	1.90(3)	2.837(3)	168(3)
b (N1L–H1L···O1D)	0.99(3)	1.84(3)	2.821(3)	169(3)
c (N1L–H3L···O2L)	0.99(4)	1.75(4)	2.728(3)	172(3)
d (N1D–H2D···O1D)	0.94(3)	1.93(3)	2.844(3)	165(3)
e (N1D–H3D···O2D)	1.12(5)	1.59(5)	2.707(3)	172(4)
f (N1D–H1D···O1L)	0.92(3)	1.93(3)	2.837(3)	173(3)

Table S11. Graph-set analysis for L-**2**/D-**1**[a]

Type of H-bond	a	b	c	d	e	f
a	$C_1^1(5)$					
b	$D_3^3(10)$ <b>a>b	$D_1^1(2)$				
c	$C_2^2(10)$ >a>c	$D_3^3(10)$ <b>c>b	$C_1^1(5)$			
d	-	$D_3^3(8)$ >b>d<b	-	$C_1^1(5)$		
e	-	$D_3^3(10)$ >b>e<b	-	$C_2^2(10)$ >d>e	$C_1^1(5)$	
f	$D_3^2(8)$ >f>a<f	$R_2^2(10)$ >b>f	$D_3^3(10)$ >f>c<f	$D_3^3(10)$ <f>d>f	$D_3^3(10)$ <f>e>f	$D_1^1(2)$

[a] Analyzed by Mercury.[4]

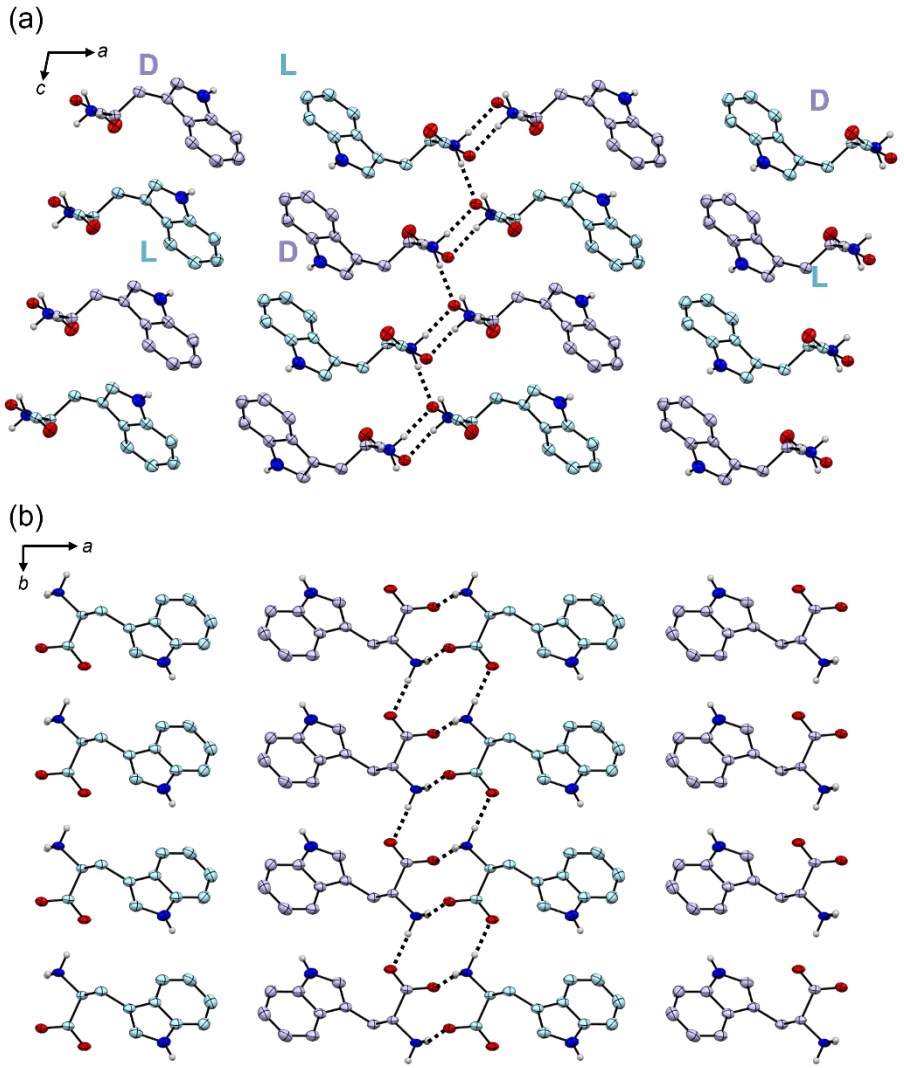

Fig. S12 Single-crystal X-ray structures of racemic crystal DL-**1** [C = light blue (L-form) and purple (D-form), N = blue, O = red]. Packing structures viewed along the (a) *b*-axis and (b) *c*-axis. Short contacts between adjacent molecules are indicated as dotted lines.

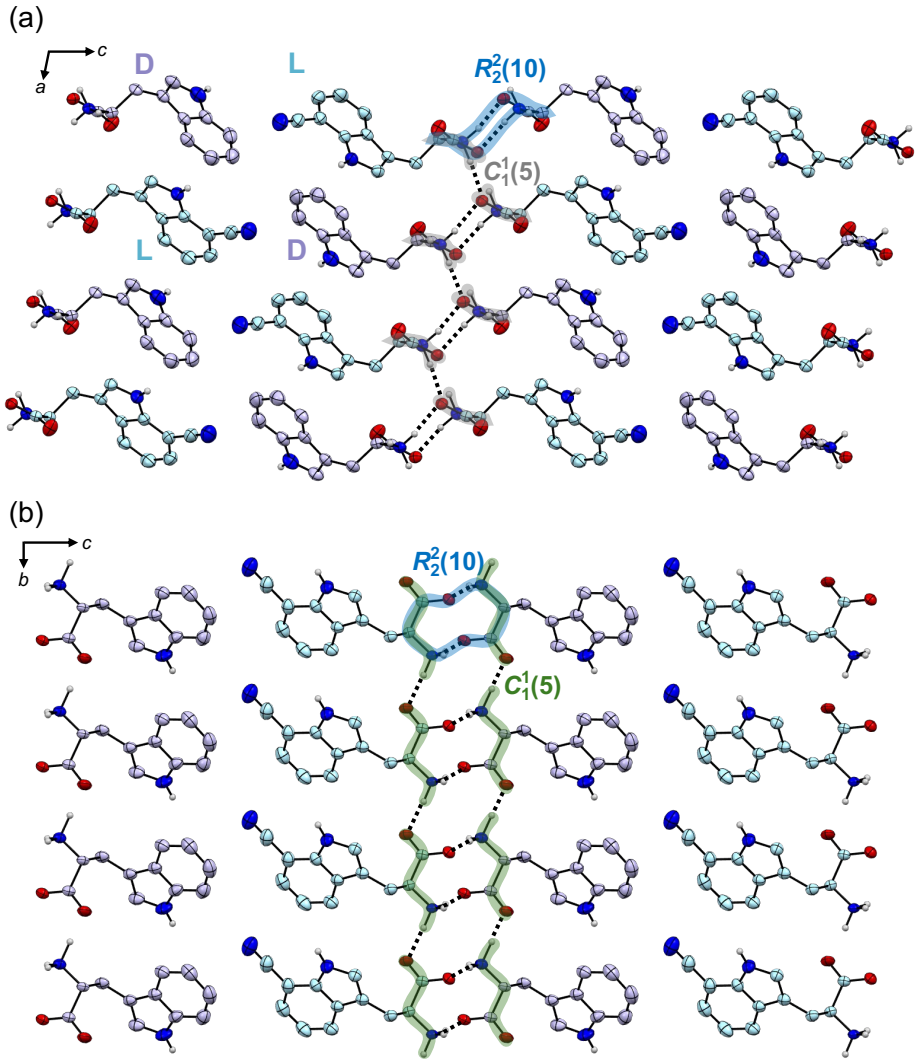

Fig. S13 Single-crystal X-ray structures of quasiracemic crystal L-**2**/D-**1** [C = light blue (L-**2**) and purple (D-**1**), N = blue, O = red]. Packing structures viewed along the (a) *b*-axis and (b) *a*-axis. Short contacts between adjacent molecules are indicated as dotted lines.

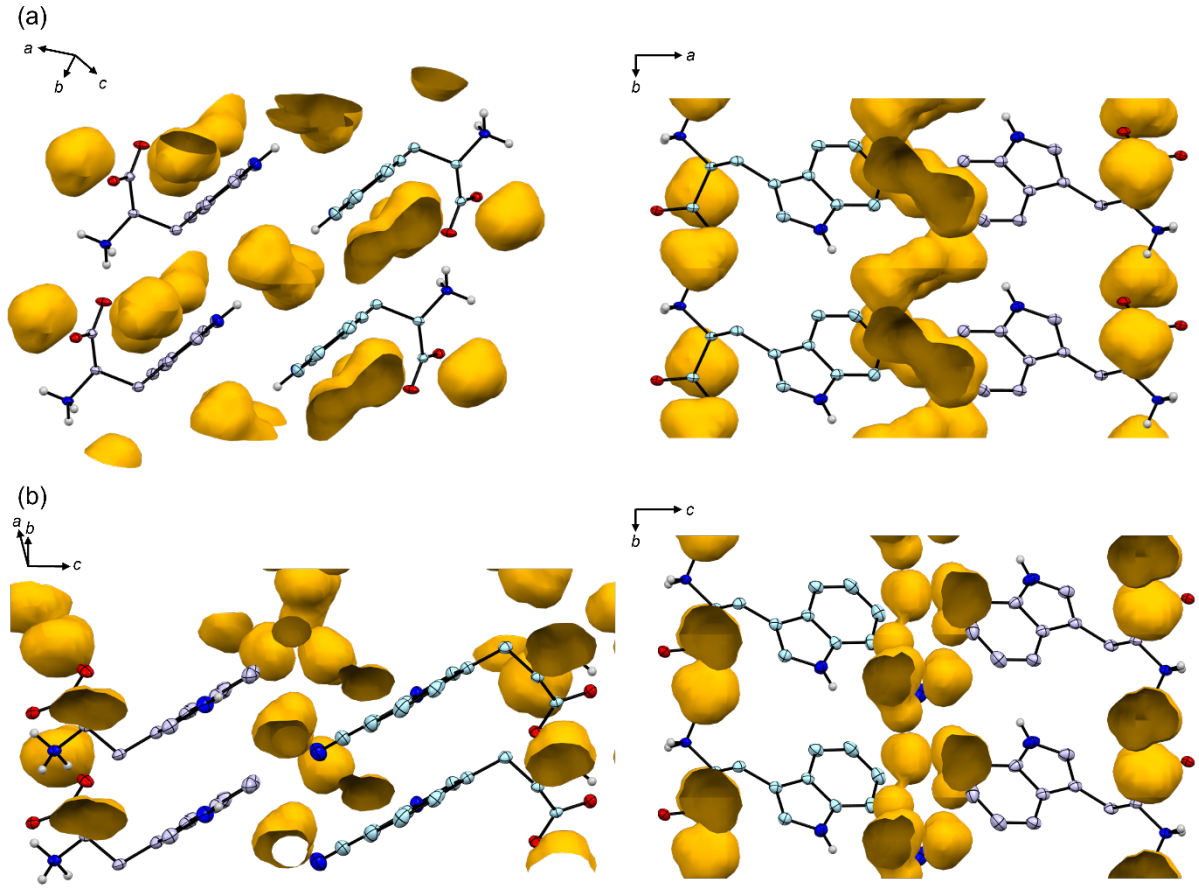

Fig. S14 Void spaces of adjacent molecules in (a) racemic crystal DL-**1** and (b) quasiracemic crystal L-**2**/D-**1** visualized in yellow using a 0.7 Å probe [C = light blue (L-form) and purple (D-form), N = blue, O = red].

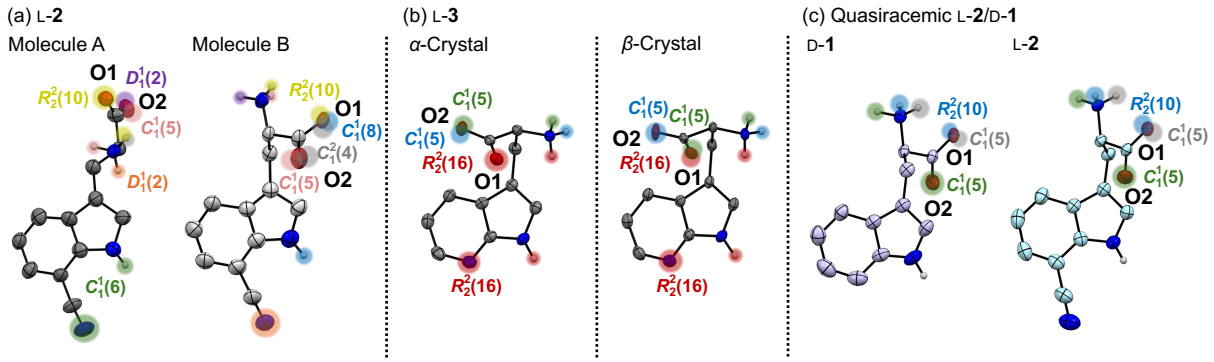

Fig. S15. Graph-set analysis for hydrogen bonds formed by each atom of (a) crystal L-**2**, (b) *α*- and *β*-crystal L-**3**, and (c) quasiracemic crystal L-**2**/D-**1**.

2. Hirshfeld surface analysis

The interactions with neighboring molecules in the crystal structures of L-**3-α** and L-**3-β** were confirmed through Hirshfeld surface analysis using the CrystalExplorer package V.21.310[6] (Fig. S16).

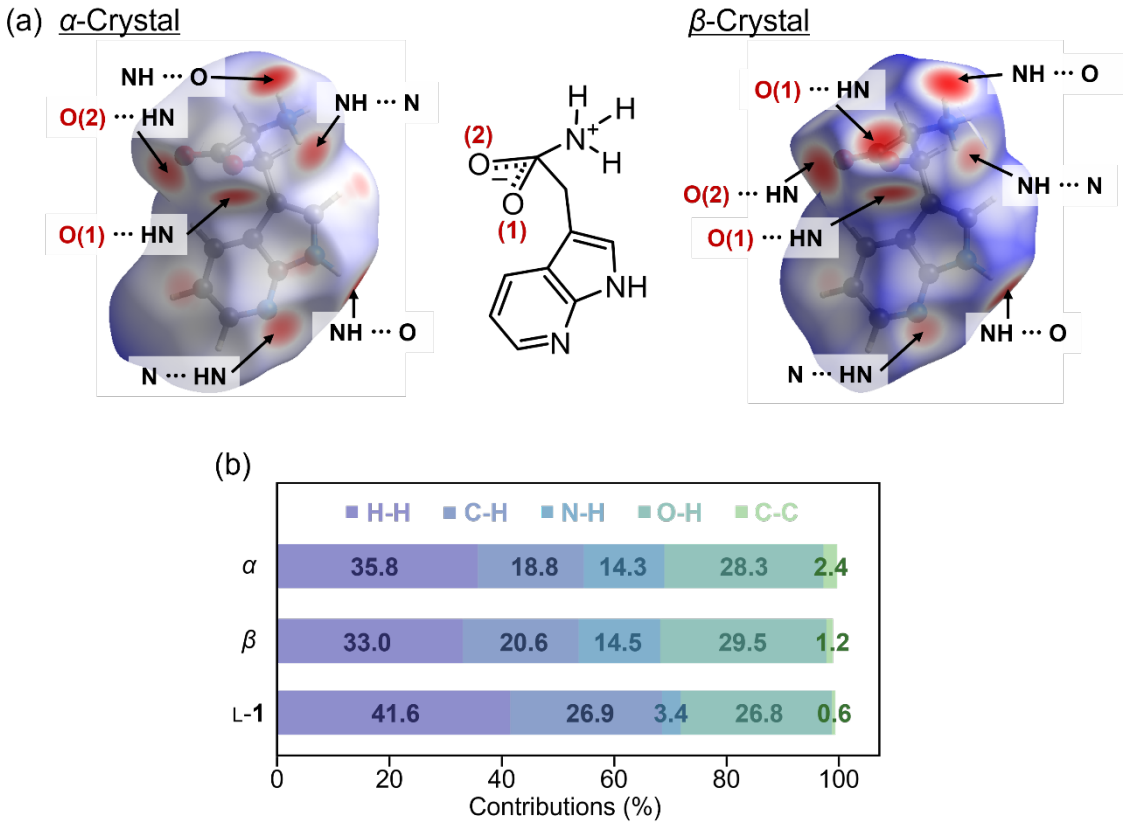

Fig. S16 (a) Hirshfeld surfaces of L-**3** within the *α*-crystal and *β*-crystal mapped with normalized contact distance (d_{norm}). Red, white, and blue areas on the surfaces indicate that the intermolecular contact distances are shorter, equal to, and longer than their van der Waals radii, respectively. (b) Individual atomic contact percentage contributions to the Hirshfeld surface in L-**3-α**, L-**3-β**, and L-**1**.

3. Bravais–Friedel–Donnay–Harker (BFDH) morphology

Bravais–Friedel–Donnay–Harker (BFDH) morphologies of L-**3-α**, L-**3-β**, DL-**1**, and L-**2**/D-**1** were obtained using Mercury (Figs S17 and S18).[4] All the crystals grew in the same direction as the continuous hydrogen bonds were formed.

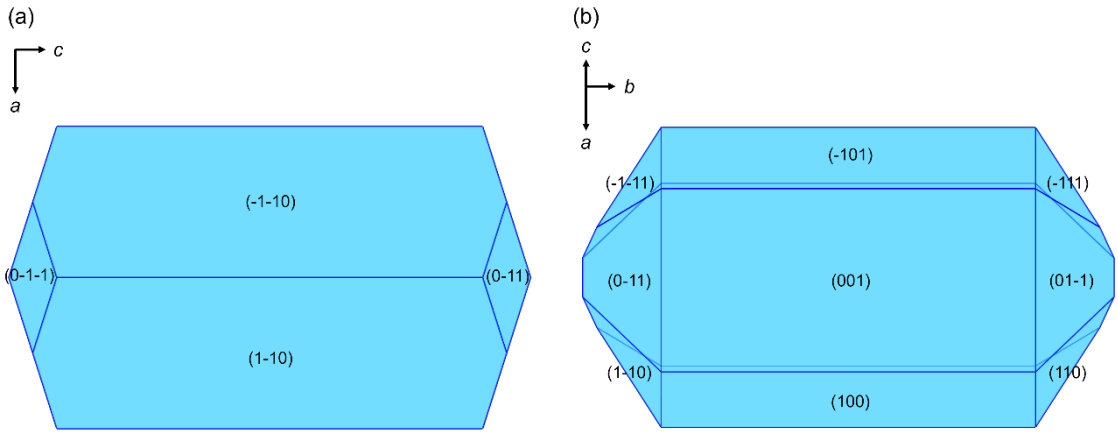

Fig. S17 BFDH morphologies of (a) L-**3-α** and (b) L-**3-β**.

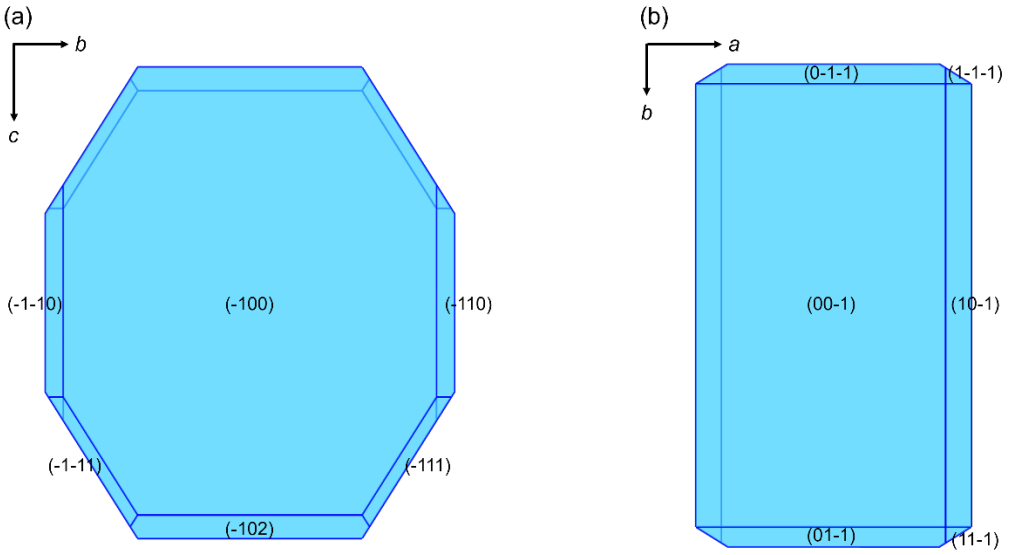

Fig. S18 BFDH morphologies of (a) DL-**1** and (b) L-**2**/D-**1**.

4. Theoretical calculations

The HOMO and LUMO of L-**2** and D-**1** calculated by time-dependent density functional theory (TD-DFT) are shown in Fig. S19.

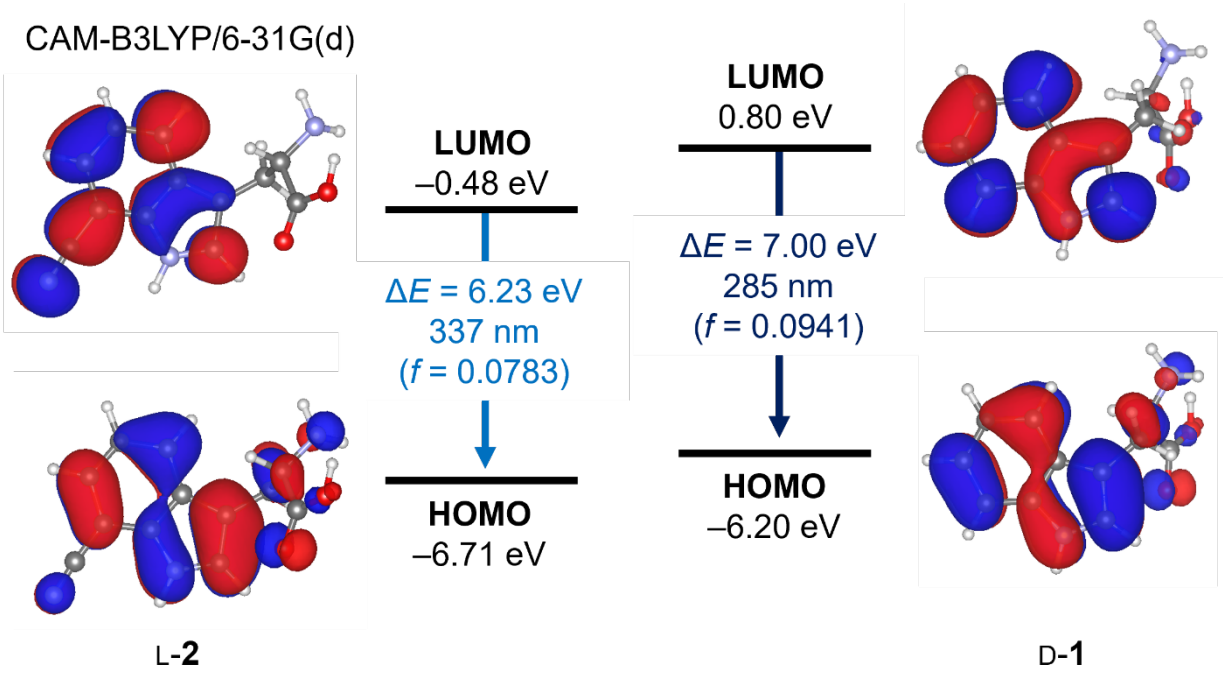

Fig. S19 Calculated fluorescence wavelengths and molecular orbitals of L-**2** and D-**1**.

5. References

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