Electronic Supplementary Material (ESI) for Organic Chemistry Frontiers.

Supporting information

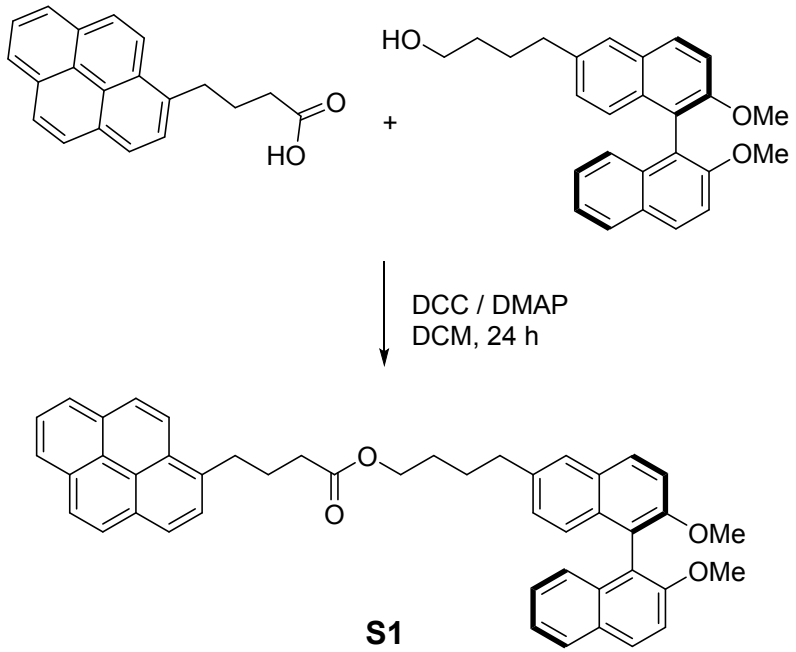
"In-Situ Immobilization" of Multicomponent Chiral Catalyst (MCC) via Non-covalent Interactions for Heterogeneous Asymmetric Hydrogenation Reactions

Contents

S1 General Information

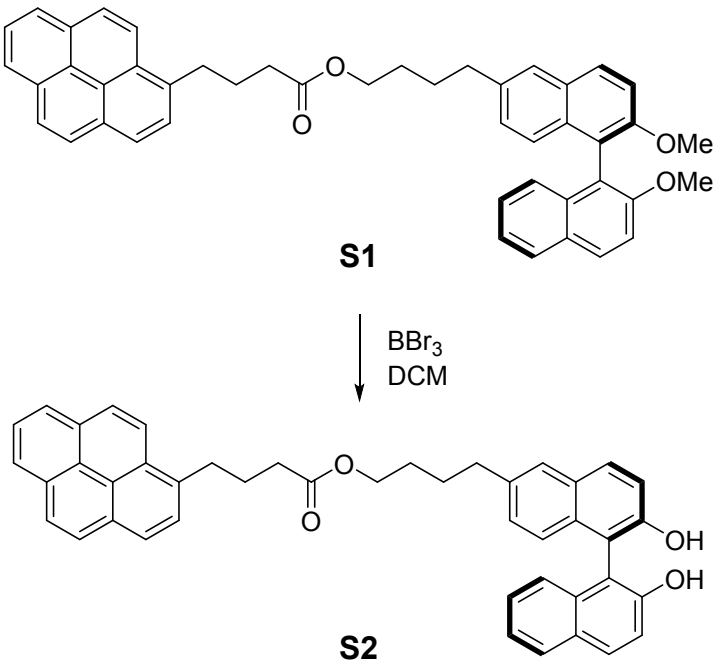
Unless otherwise noted, all reactions of substrates preparation were conducted in flame-dried glassware under a nitrogen atmosphere using anhydrous solvent passed through an activated alumina column (Innovative Technology). Commercially available reagents were used without further purification. Thin layer chromatography (TLC) was performed using Huanghai TLC silica gel plates HSG F254 and visualized using UV light, anisaldehyde or potassium permanganate. 1H and 13C NMR spectra were recorded in $CDCl_3$ on a Bruker Advance III-400 spectrometer. Chemical shifts in ^1H NMR spectra were reported in parts per million (ppm) on the δ scale from an internal standard of residual $CDCl_3$ (7.26 ppm). Data for ^1H NMR were reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad), coupling constant in Hertz (Hz) and integration. Data for ^{13}C NMR spectra were reported in terms of chemical shift in ppm from the central peak of $CDCl_3$ (77.00 ppm). IR spectra were recorded on a Bruker Tensor 27 spectrometer and only major peaks are reported in cm^{-1}. HRMS were obtained on a Q-TOF micro spectrometer. ICP analysis of Rh leaching was performed with Agilent 7500a. Liquid chromatographic analyses were conducted on a Waters HPLC system and Breeze workstation.

S2 Preparation of ligand 2

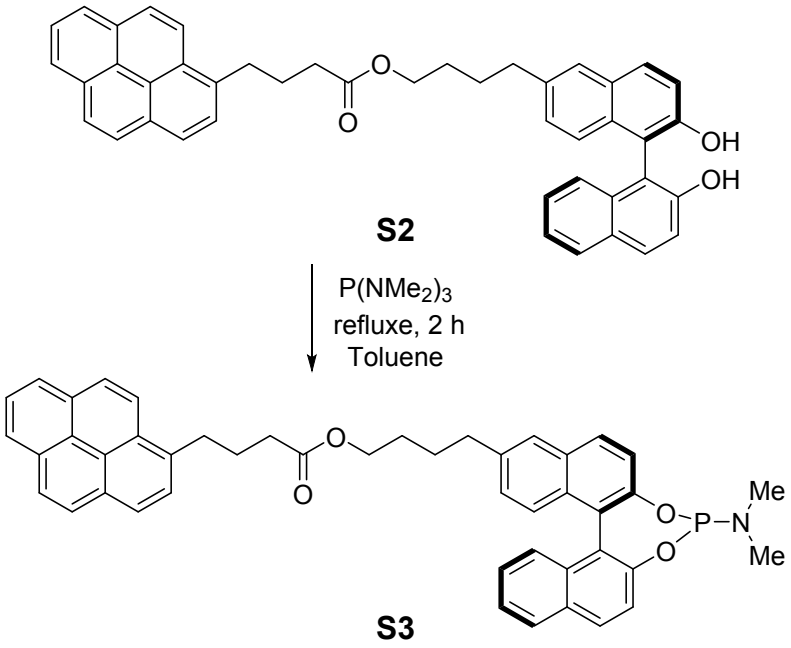


S1

A solution of 1-Pyrenebutyric acid (224 mg, 0.78 mmol), (R)-[1,1'-Binaphthalene]-2,2'-dimethoxy-6-butanol (300 mg, 0.78 mmol), DCC (320 mg, 1.55 mmol) and DMAP (190 mg, 1.55 mmol) in CH_2Cl_2 (8mL) was stirred at room temperature for 24 h. The reaction mixture was quenched with celite, stirred for 1 h, filtered and concentrated in vacuo to afford pale yellow oil，the crude product was purified by silica gel column chromatography [EtOAc-Petroleum ether (1:10)] to yield S**1** (480 mg, 94%) as a pale yellow solid. mp: 72℃; [R] = +30.6° (20℃, c=0.01 g/ml, DCM). ^{1}H NMR(400 MHz, $CDCl_3$) δ 8.32 (d, *J* = 9.1 Hz, 1H), 8.19 – 8.14 (m, 2H), 8.13 – 8.06 (m, 2H), 8.07– 7.95 (m, 4H), 7.94 – 7.82 (m, 3H), 7.65 (s, 1H), 7.49 – 7.41 (m, 2H), 7.38 – 7.31 (m, 1H), 7.25 – 7.22 (m, 1H), 7.19 – 7.15 (m, 1H), 7.08 (s, 2H), 4.23 – 4.14 (m, 2H), 3.77 (s, 6H), 3.40 (t, *J* = 7.4 Hz, 2H), 2.76 (t, *J* = 7.4 Hz, 2H), 2.49 – 2.45 (m, 2H), 2.25 – 2.21 (m, 2H), 1.89 – 1.61 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 155.0, 154.6, 137.0, 135.7, 134.0, 132.5, 131.4, 130.9, 129.9, 129.4, 129.3, 129.2, 128.7, 127.9, 127.7, 127.4, 127.3, 127.3, 126.6, 126.4, 126.2, 125.8, 125.3, 125.3, 125.1, 125.0, 124.8, 124.8, 124.7, 123.4, 123.3, 119.8, 119.6, 114.4, 114.2, 64.3, 56.9, 56.8, 35.3, 33.9, 32.7, 28.3, 27.5, 26.8. HRMS (EI+) Calculated for $C46H40O4Na^{+1}$ [M^++Na]: 679.2819, Found: 679.2821.



To a cooled (-78℃) solution of **S1** (200 mg, 0.3 mmol) in anhydrous CH_2Cl_2 (2 mL), 1.0 M CH_2Cl_2 solution of BBr_3 (0.66 mL, 0.66 mmol) was added drop wise. The mixture was warmed over 2 h at room temperature, stirred for a further 1.5 h, and then poured carefully into saturated aqueous $NaHCO_3$ (5 mL). The layers were separated, and the organic phase was extracted with CH_2Cl_2 (3 × 5 mL). The combined organic layers were dried over anhydrous Na_2CO_3, and the solvent was evaporated to yield the crude product as a yellow oil. silica gel column chromatography [EtOAc-Petroleum ether (1:5)] yielded **S2** (0.69 g, 75%) as a pale yellow solid. mp: 98-102℃; [R] = -23.6° (20℃, c=0.01g/ml, DCM). ^{1}H NMR(400 MHz, $CDCl_3$): δ 8.29 (d, J = 9.2 Hz, 1H), 8.18 – 8.12 (m, 2H), 8.13 – 8.11 (m, 3H), 8.01 (d, J = 5.5 Hz, 2H), 7.97 (d, J = 8.5 Hz, 2H), 7.92 – 7.81 (m, 3H), 7.64 (s, 1H), 7.41 – 7.33 (m, 3H), 7.30 (dd, J = 14.4, 6.2 Hz, 1H), 7.18 – 7.12 (m, 1H), 7.12 – 7.05 (m, 1H), 5.07 (br.s, 2H), 4.16 – 4.04 (m, 2H), 3.38 (t, J = 7.7 Hz, 2H), 2.73 (t, J = 7.2 Hz, 2H), 2.44 (t, J = 7.2 Hz, 2H), 2.19 (p, J = 7.3 Hz, 2H), 1.77 – 1.64 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.8, 153.0, 152.5, 138.9, 135.9, 133.7, 132.1, 131.7, 131.6, 131.1, 131.0, 130.2, 129.9, 129.7, 129.0, 128.6, 127.7, 127.7, 127.6, 127.6, 127.3, 126.9, 126.1, 125.3, 125.2, 125.1, 125.0, 125.0, 124.5, 124.5, 124.2, 123.5, 118.0, 111.3, 111.1, 111.0, 64.5, 35.5, 34.2, 33.0, 28.5, 27.9, 27.0. HRMS (EI+) Calculated for $C44H36O4Na^{+1}$ [M^++Na]: 651.2511, Found: 651.2499.



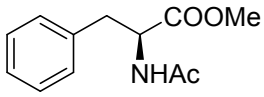
An oven-dried, cooled under N_2 atmosphere round bottomed flask equipped with a reflux condenser was charged with **S2** (0.5 g, 0.8 mmol) and flushed with N_2. To this solid dry toluene was added (5 mL) followed by $P(NMe_2)_3$ (0.8 mmol, 0.15 mL). The reaction mixture was then refluxed for 2 h. ^{31}P NMR analysis of the cooled reaction mixture showed the sole formation of the desired phosphoramidite product (δ 148.8). The crude reaction mixture was concentrated and purified via silica gel column chromatography (Hexane:CH_2Cl_2, 100%, Rf = 0.5). The product was isolated as a white powder **S3** (95%). mp: 110-113℃; [R] = -304.6° (20℃, c=0.01g/ml, DCM) ^1H NMR(400 MHz $CDCl_3$) δ 8.30 (d, *J* = 9.2 Hz, 1H), 8.18 – 8.12 (m, 2H), 8.09 (d, *J* = 9.2 Hz, 2H), 8.03 – 7.93 (m, 3H), 7.87 (dd, *J* = 8.5, 7.3 Hz, 1H), 7.88 – 7.96 (m, 2H), 7.65 (s, 1H), 7.52 – 7.42 (m, 2H), 7.43 – 7.46 (m, 1H), 7.36 – 7.30 (m, 1H), 7.29 – 7.14 (m, 3H), 7.12 – 7.05 (m, 1H), 4.13 (q, *J* = 6.0 Hz, 2H), 3.39 (t, *J* = 7.7 Hz, 2H), 2.79 – 2.71 (m, 2H), 2.55 (dd, *J* = 8.9, 4.5 Hz, 6H), 2.46 (t, *J* = 7.2 Hz, 2H), 2.20 (p, *J* = 7.2 Hz, 2H), 1.83 – 1.59 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.5, 148.4, 137.4, 137.1, 134.7, 130.4, 129.9, 128.9, 128.0, 127.7, 127.2, 127.1, 126.4, 126.4, 126.3, 126.3, 126.0, 125.8, 125.7, 125.7, 125.0, 124.8, 124.3, 124.1, 124.0, 123.9, 123.8, 123.7, 123.7, 123.5, 122.3, 121.0, 120.9, 63.2, 35.0, 34.8, 32.9, 31.7, 29.9, 27.3, 26.5, 25.8. HRMS (EI+) Calculated for C46H40NO4P $[M]^+$: 701.2695, Found: 701.5168.

S3 Hydrogenation.

For example, **2a**@graphene (0.01 mmol, 10 mM, based on the $(Monophos)_2$/Rh unit), **6** (1 mmol, 1.0 M) in anhydrous ethyl acetate (5.0 mL) were placed in a test tube under argon atmosphere. The test tube was placed in a stainless steel autoclave, and then sealed. After purging with hydrogen for 3 times, final H_2 pressure was adjusted to 20 atm and stirring commenced. Following a period of 2 h, H_2 was released and the catalyst recovered by cannula filtration under an argon atmosphere. The product was analyzed following removal of ethyl acetate under the reduced pressure. Conversion and enantiomeric excess were determined by 1 H NMR and chiral HPLC (Chiralpak IA column), respectively.

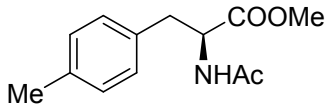
S4 ^{1}H NMR and ^{13}C NMR of products

7a



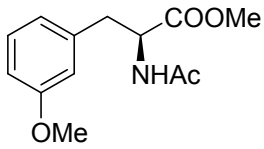
Methyl 2-acetamido-3-phenyl propanoate. white solid.[3] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.99 (s, 3H; CH_3CO), 3.07-3.18 (m, 2H; CH_2), 3.73 (s, 3H; OCH_3), 4.87-4.91 (m, 1H; CH), 5.91 (d, J=7.2HZ, 1H; NH), 7.08-7.12 (m, 2H; ArH), 7.25-7.31 (m, 3H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml), minor t1 = 18.28 min; major t2 = 22.20 min; 95 % ee.

7b



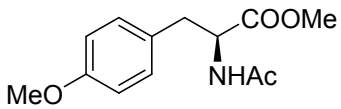
Methyl 2-acetamido-3-(p-tolyl) propanoate. white solid. [4,5]^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.97 (s, 3H; CH_3CO), 2.31 (s, 3H; $ArCH_3$), 3.01-3.07 (m, 2H; CH_2), 3.72 (s, 3H; $COOCH_3$), 4.83-4.88 (m, 1H; CH), 6.00 (d, J = 7.2 Hz, 1H; NH), 6.96 (d, J = 7.9 Hz, 2H; ArH), 7.09 (d, J = 7.8 Hz, 2H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml) , minor t1 = 20.40min; major t2 = 25.20 min; 93% ee.

7c



Methyl 2-acetamido-3-(3-methoxyphenyl) propanoate. white solid.[5] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.99 (s, 3H; CH_3CO), 3.04-3.11 (m, 2H; CH_2), 3.73 (s, 3H; $ArOCH_3$), 3.78 (s, 3H; $COOCH_3$), 4.85-4.90 (m, 1H; CH), 5.93 (d, J = 7.2 Hz, 1H; NH), 6.62-6.66 (m, 2H; ArH), 6.79 (dd, J=8.1Hz，1H; ArH), 7.20 (t, J = 7.9 Hz, 1H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml), minor t1 = 29.36 min; major t2 = 33.78 min; 93% ee.

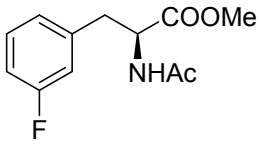
7d



Methyl 2-acetamido-3-(4-methoxyphenyl) propanoate. white solid. [3,4,5]^{1}H NMR (400 MHz, $CDCl_3$,): δ = 1.99

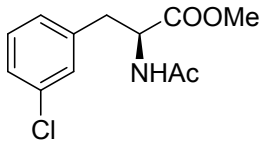
(s, 3H; CH_3CO), 3.02-3.11 (m, 2H; CH_2), 3.73 (s, 3H; OCH_3), 3.78 (s, 3H; $COOCH_3$), 4.84-4.89 (m, 1H; CH), 5.93 (d, J = 7.2 Hz, 1H; NH), 6.96 (d, J = 8.4 Hz, 2H; ArH), 7.41 (d, J = 6.9 Hz, 2H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml) , minor t1=20.54 min; major t2 = 25.56 min; 96% ee.

7e



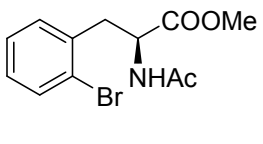
Methyl 2-acetamido-3-(4-fluorophenyl) propanoate. yellow solid.[4,5] ^1H NMR (400 MHz, $CDCl_3$): δ = 2.00 (s, 3H; CH_3CO), 3.06-3.15 (m, 2H; CH_2), 3.74 (s, 3H; $COOCH_3$), 4.86-4.91 (m, 1H; CH), 5.96 (d, J = 7.2Hz, 1H; NH), 6.80 (dd, J=9.7Hz, 1H; ArH), 6.87 (dd, J=7.6Hz, 1H; ArH), 6.92-6.95 (m, 1H; ArH), 7.23-7.28 (m, 1H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml), minor t1 = 20.40 min ; major t2 = 25.20 min; 93% ee.

7f



Methyl 2-acetamido-3-(3-chlorophenyl) propanoate. yellow solid.[4,6] ^1H NMR (400 MHz, $CDCl_3$,): δ = 1.99 (s, 3H; CH_3CO), 3.07-3.12 (m, 2H; CH2), 3.73 (s, 3H; OCH_3), 4.86-4.90 (m, 1H; CH), 5.98 (d, J = 7.2Hz, 1H; NH), 7.08-7.11 (m, 1H; ArH), 7.12 (s, 1H; ArH), 7.27-7.29 (m, 2H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml), minor t1 = 20.54 min; major t2 = 25.11 min; 94% ee.

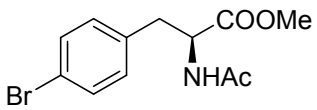
7g



Methyl 2-acetamido-3-(2-bromophenyl)propanoate. yellow solid.[6] ^1H NMR (400 MHz, CDCl3): δ = 1.88 (s, 3H; CH_3CO), 3.07-3.28 (m, 2H; CH2), 3.65 (s, 3H; OCH_3), 4.81-4.88 (m, 1H; CH), 6.05 (d, J = 7.2 Hz, 1H; NH), 7.01-7.07 (m, 1H; ArH), 7.11-7.20 (m, 2H; ArH), 7.46 (d, J = 7.8 Hz, 1H; ArH); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 171.1, 168.7, 134.9, 132.0 130.2, 127.8, 126.6, 124.0, 51.5, 51.5, 36.9, 22.1; Enantiomeric excess was

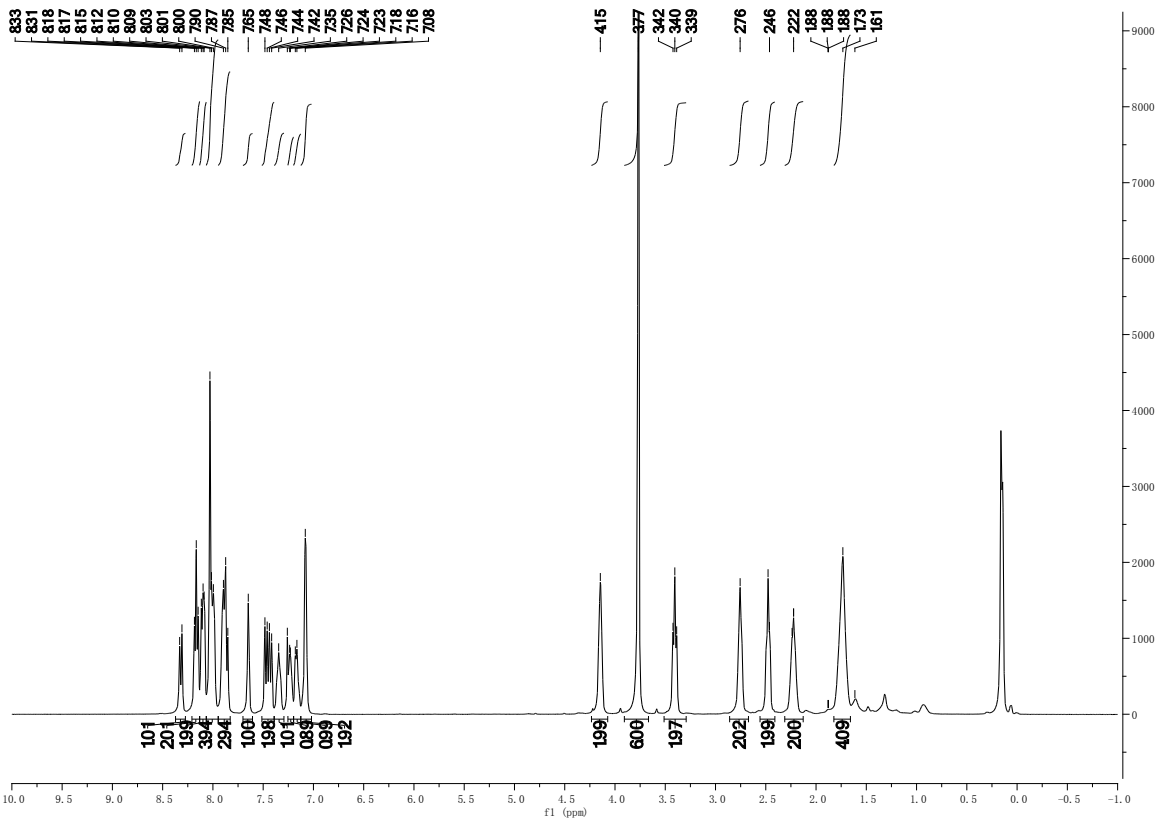
determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml) , minor t1 = 29.30 min; major t2 = 35.89 min; 91% ee.

7h

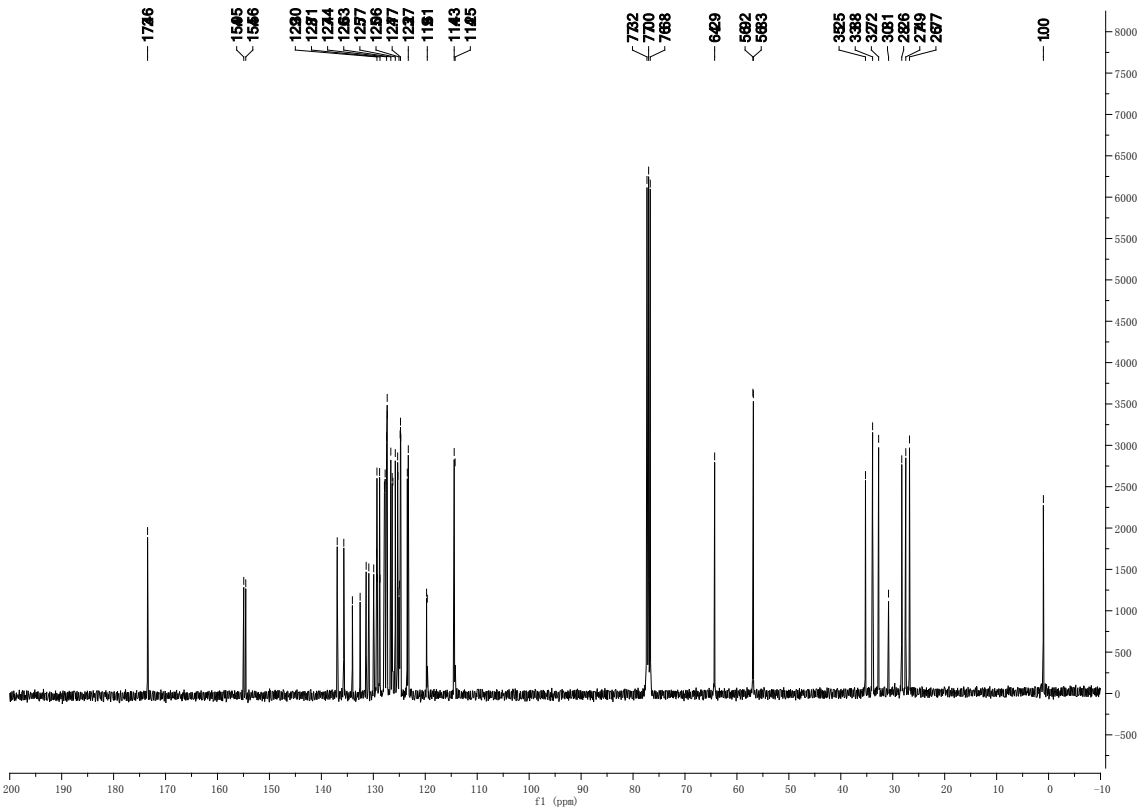


Methyl 2-acetamido-3-(4-bromine) propanoate. yellow solid.[5,6] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.99 (s, 3H; CH_3CO), 3.02-3.11 (m, 2H; CH_2), 3.73 (s, 3H; $COOCH_3$), 4.84-4.89 (m, 1H; CH), 5.94 (d, J = 7.2 Hz, 1H; NH), 6.96 (d, J = 7.8 Hz, 2H; ArH), 7.41 (d, J=6.8Hz, 2H; ArH); Enantiomeric excess was determined by HPLC with a Chiralpak IA column (4.6mmΦ × 250mml) , minor t1 = 25.40 min; major t2 = 32.26 min; 91% ee.

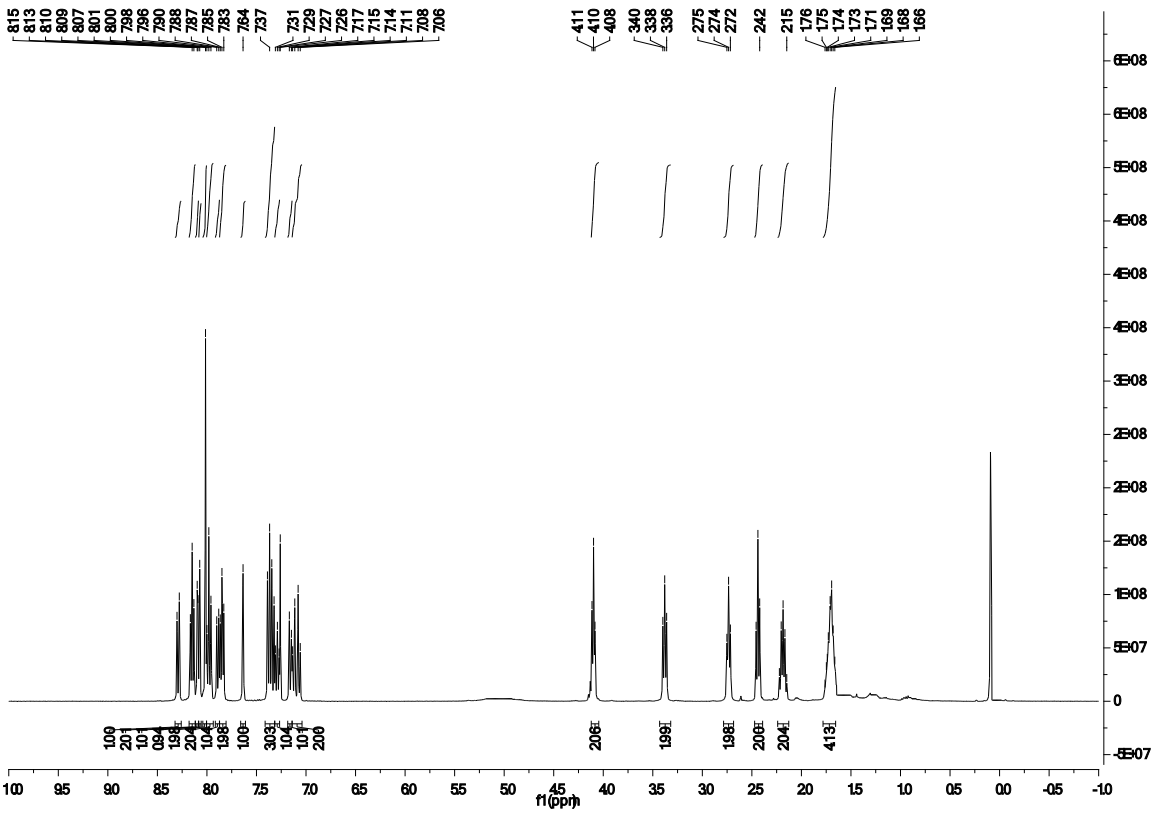
^{1}H-NMR of **S1** in $CDCl_3$



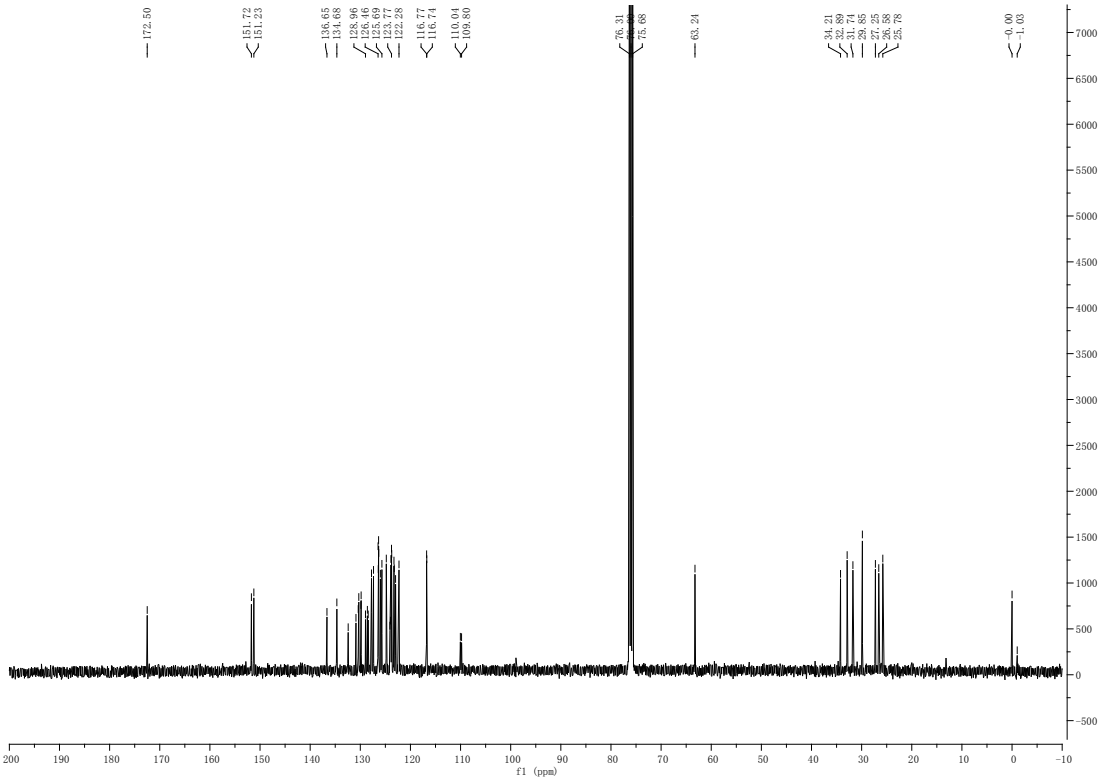
^{3}C-NMR of **S1** in $CDCl_3$



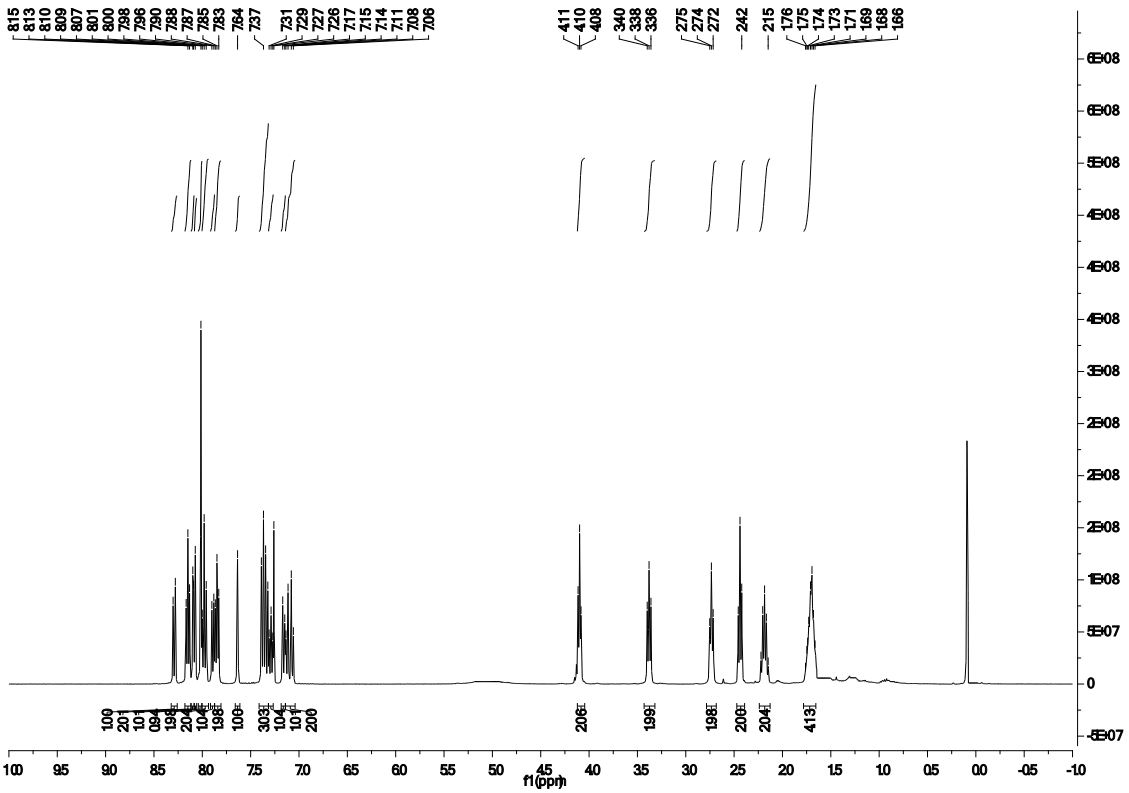
^{1}H-NMR of **S2** in $CDCl_3$



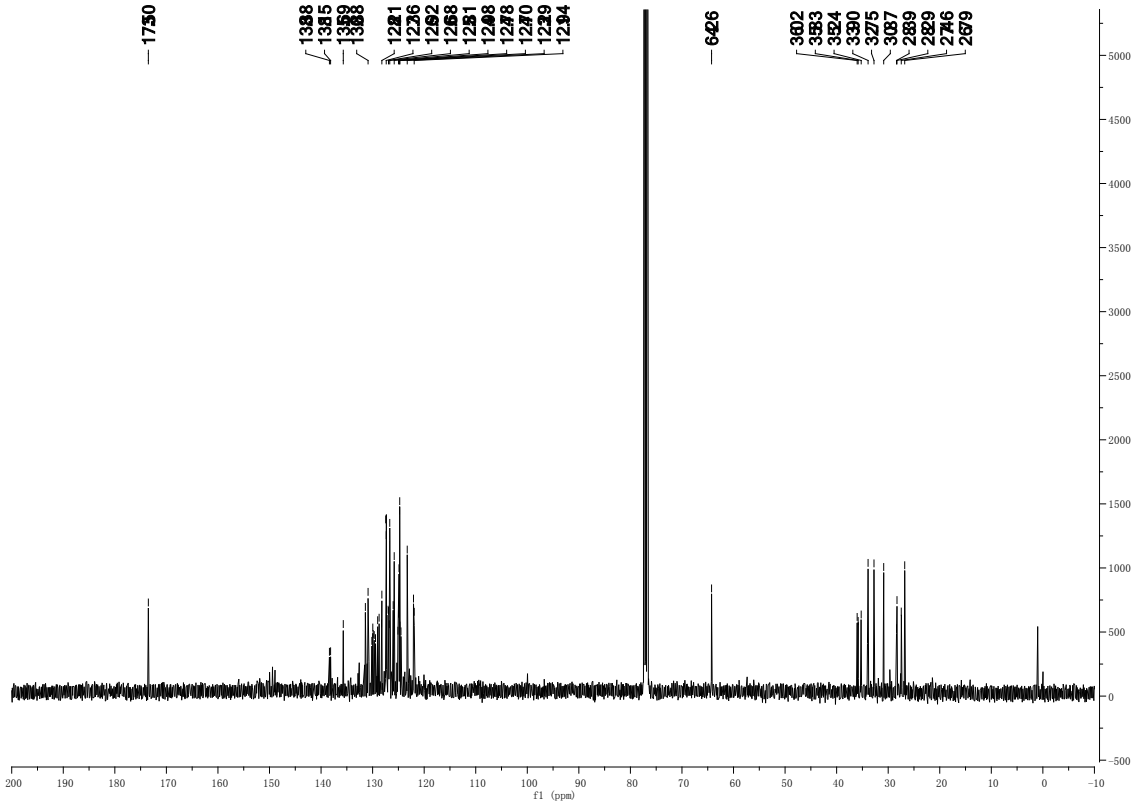
^{13}C-NMR of **S2** in $CDCl_3$



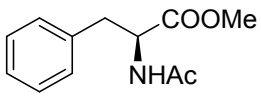
^{1}H-NMR of **S3** in $CDCl_3$



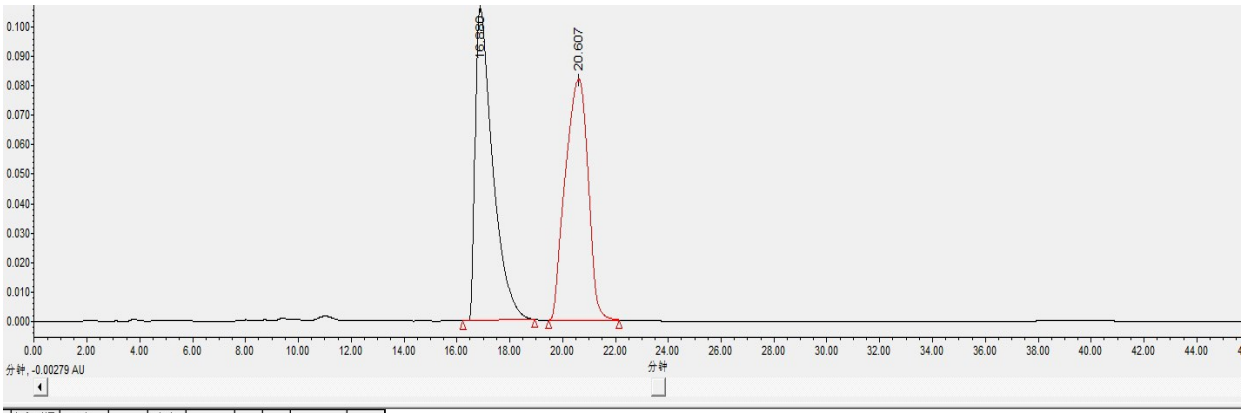
^{13}C-NMR of **S3** in $CDCl_3$



S5 Chiral HPLC analysis of products 7a-7h



7a



保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
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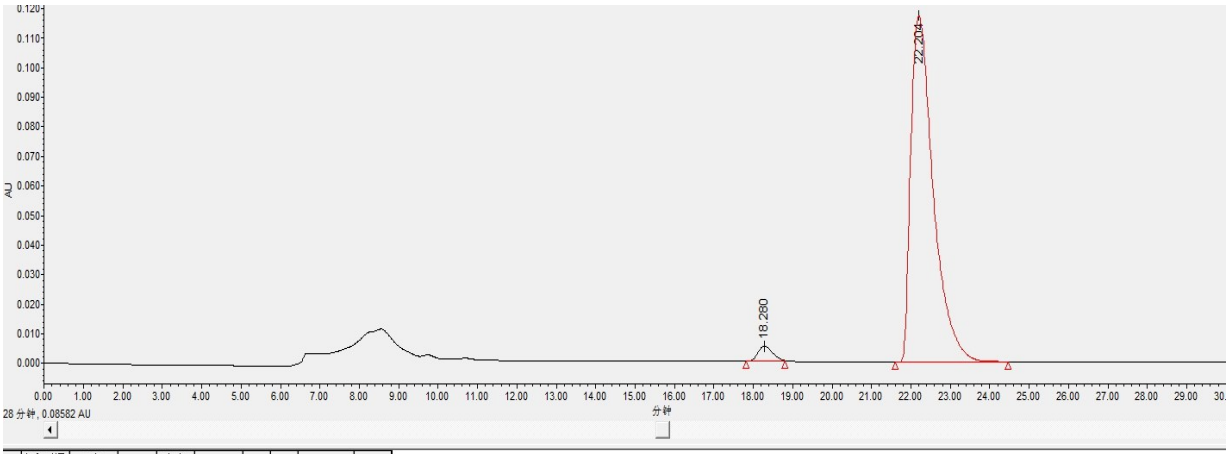
20.607	4891172	50.02	81876	bb			未知	



保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
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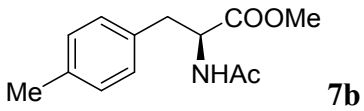
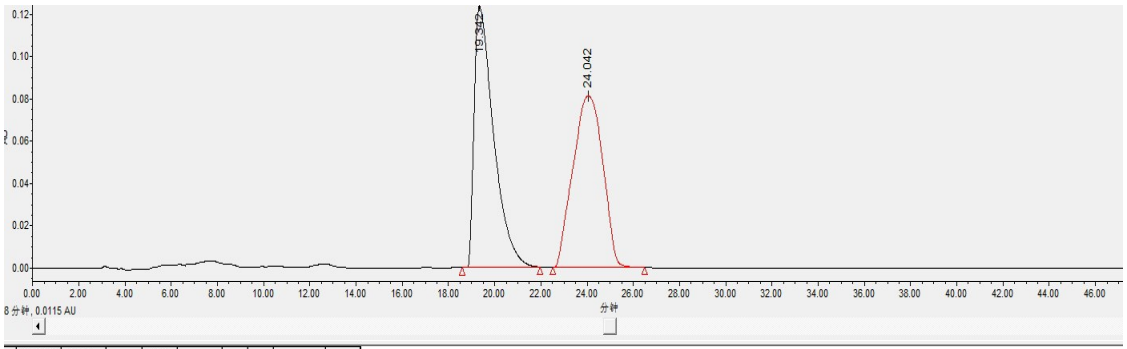
22.204	4640089	97.41	117205	bb			未知	



7b



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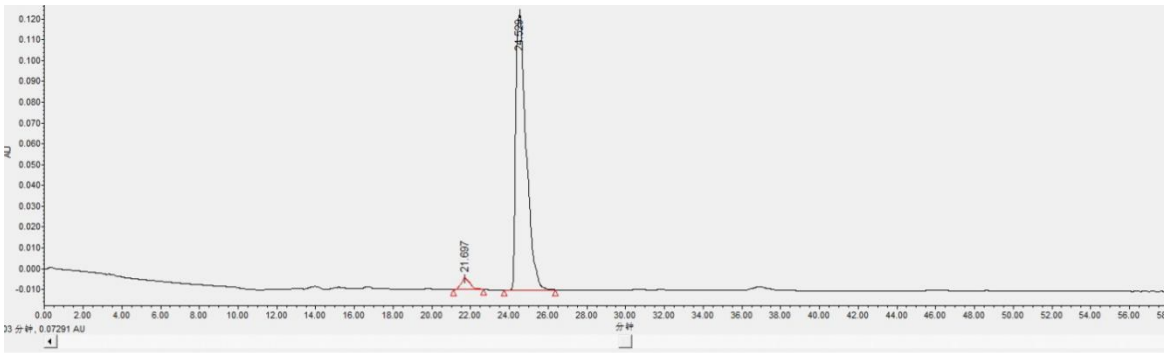
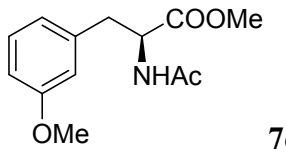
	19.342	7234845	49.89	123399	bb			未知	
	24.042	7265704	50.11	81095	bb			未知	



称	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
	21.697	176438	3.41	5514	bb			未知	
	24.529	4990509	96.59	132818	bb			未知	



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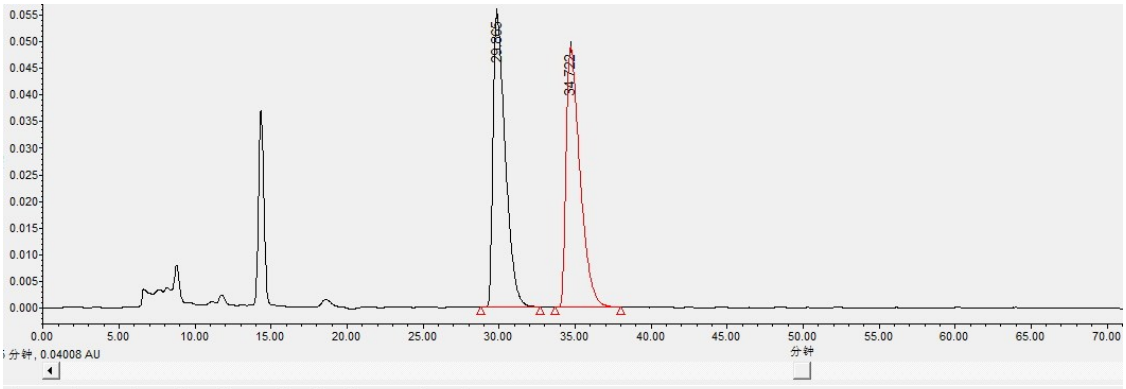
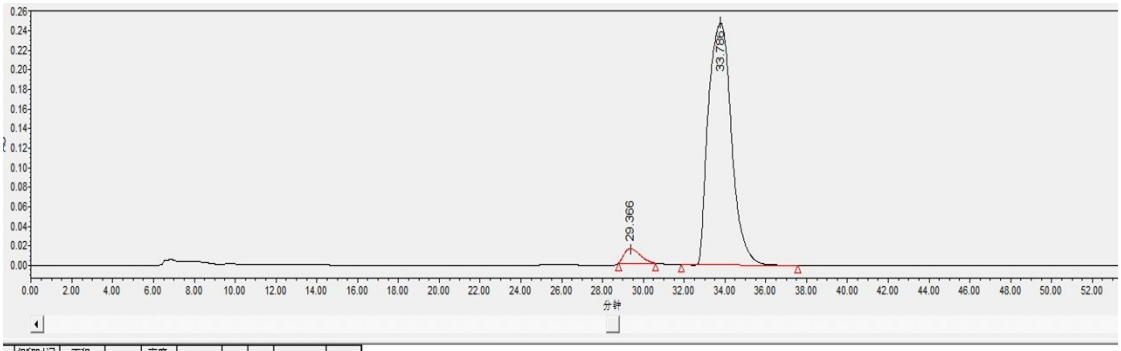
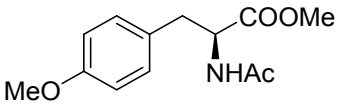


	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
	29.865	3100740	49.91	55171	bb			未知	
	34.722	3112350	50.09	48988	bb			未知	



	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
	29.366	805736	3.97	14778	bb			未知	
	33.786	19481948	96.03	247642	bb			未知	



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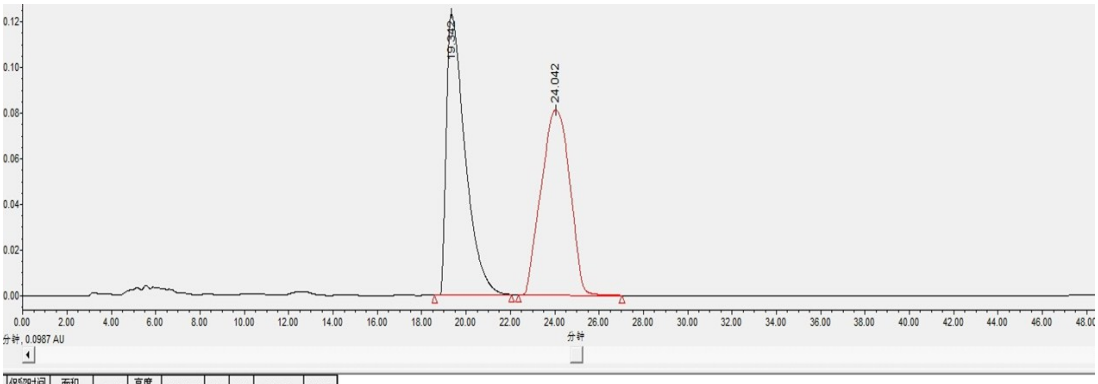

保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
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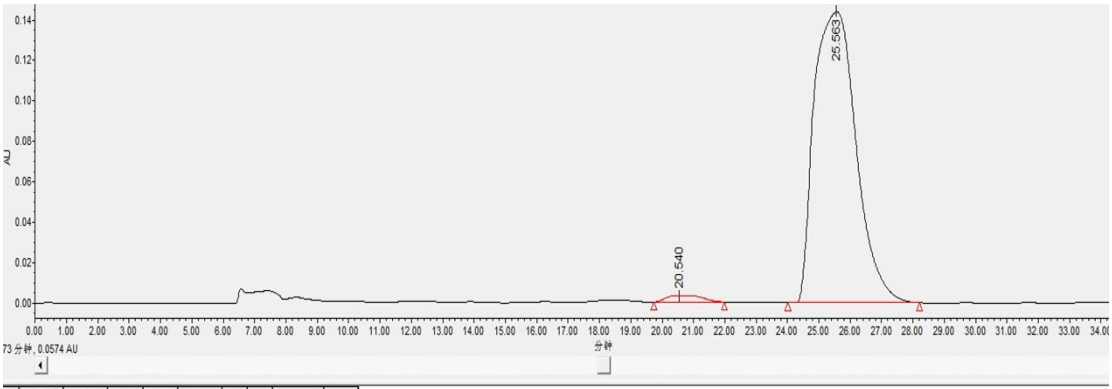
24.042	7288496	50.16	81171	bb			未知	



峰	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
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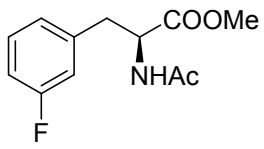
	25.563	13435124	98.17	144011	bb			未知	



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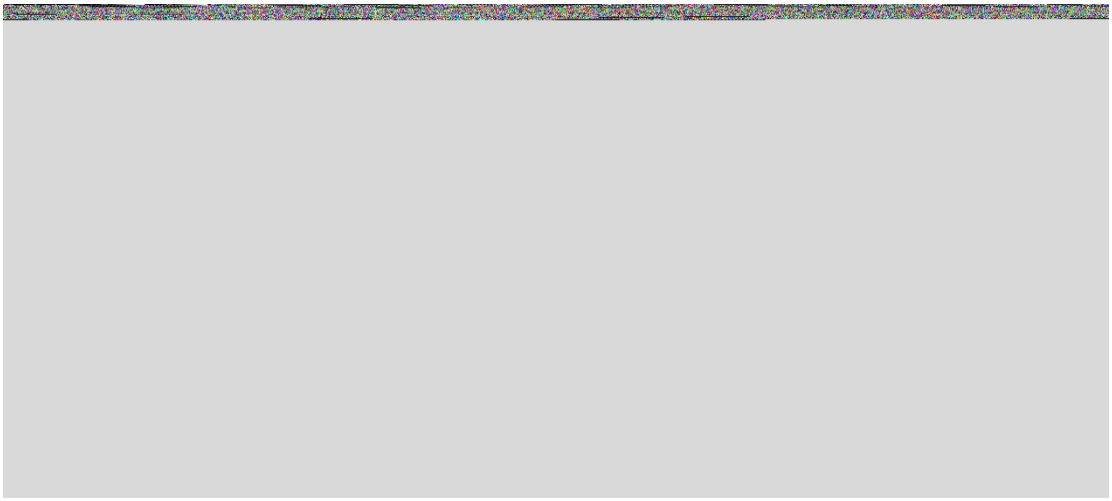
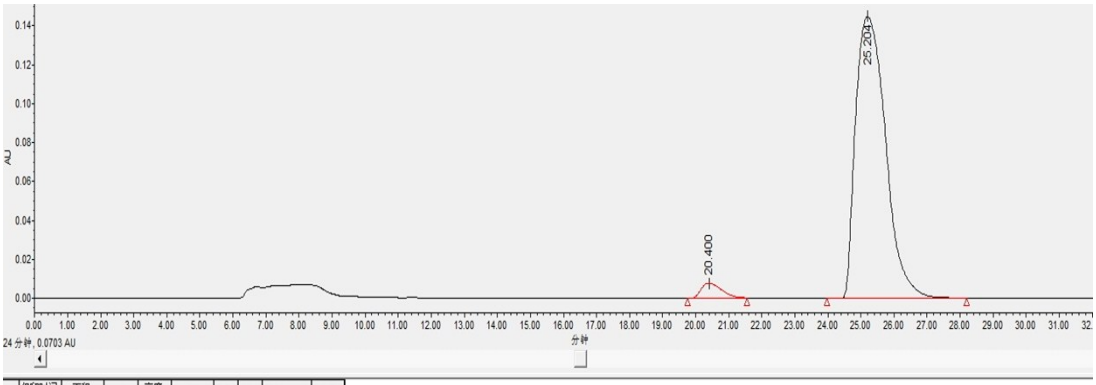
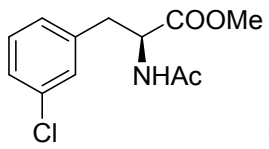




称	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
	20.400	332031	3.51	7744	bb			未知	
	25.204	9120487	96.49	144714	bb			未知	



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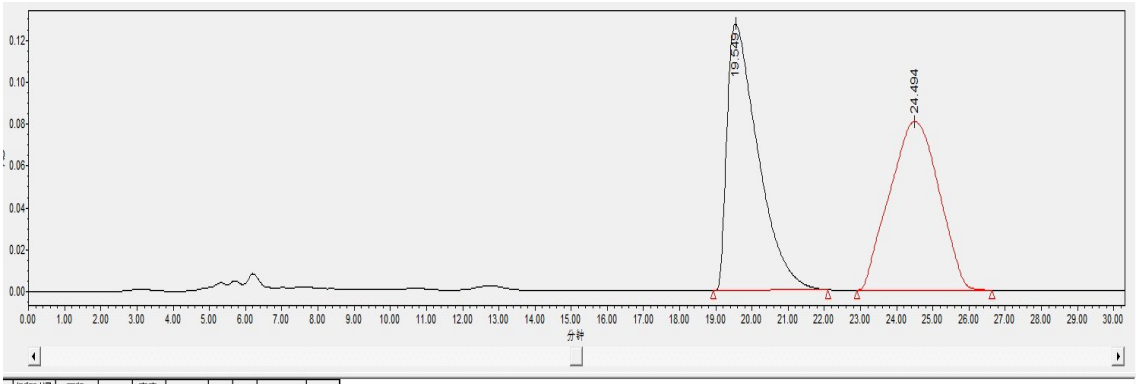
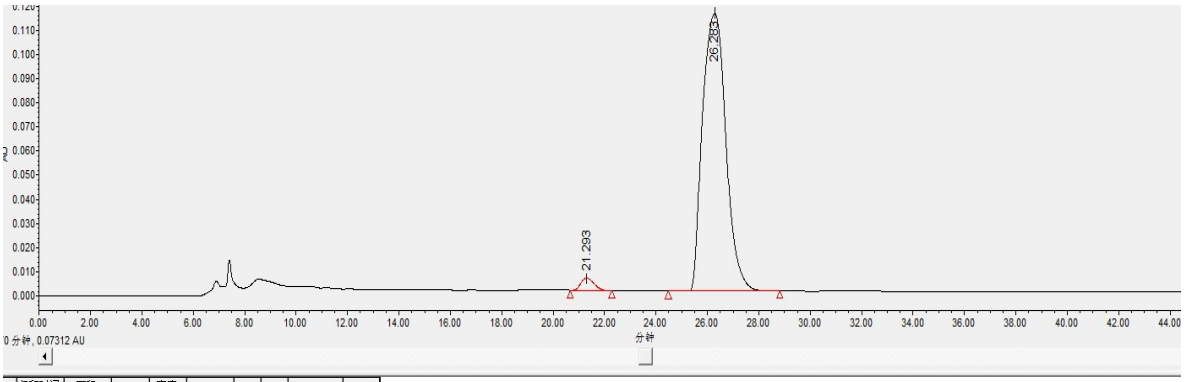
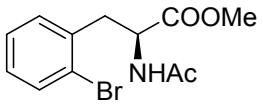


保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
19.549	7591254	49.83	127142	bb			未知	
24.494	7643866	50.17	80590	bb			未知	



保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
21.293	181893	2.45	5100	bb			未知	
26.283	7250151	97.55	114817	bb			未知	



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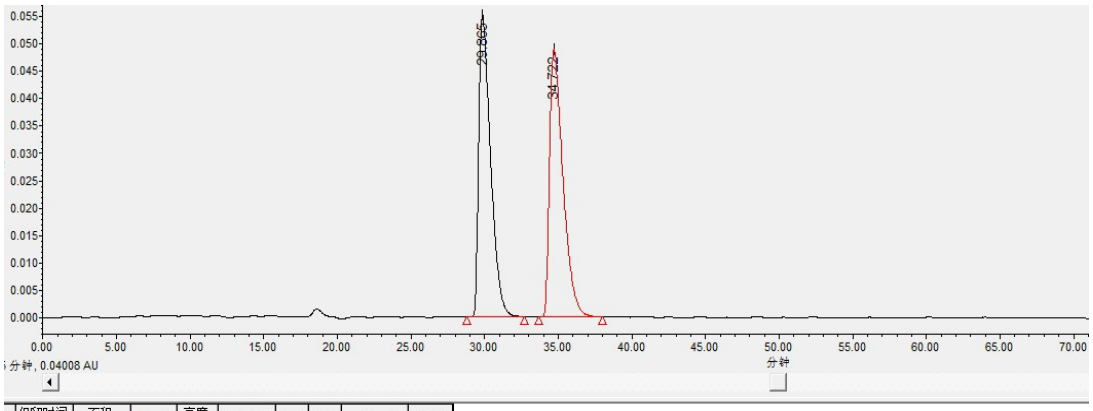
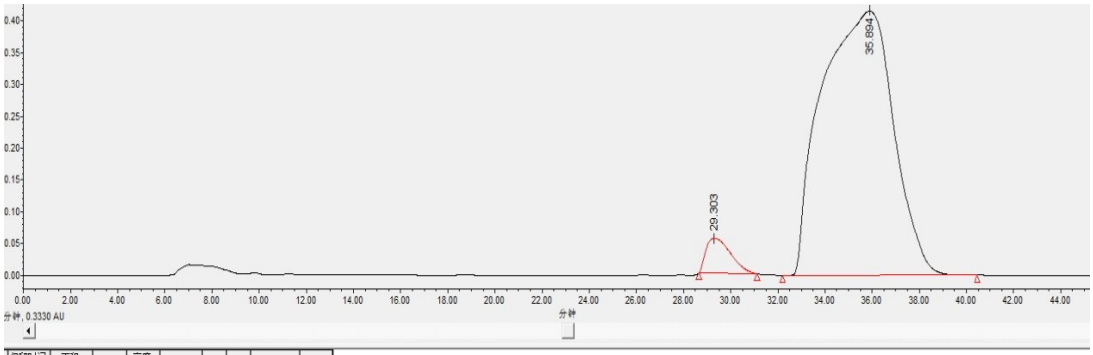
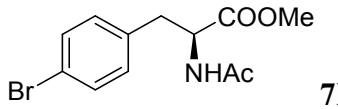


保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
29.865	3100740	49.91	55171	bb			未知	
34.722	3112350	50.09	48988	bb			未知	



保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
29.303	3985529	4.35	54874	bb			未知	
35.894	87592811	95.65	414979	bb			未知	



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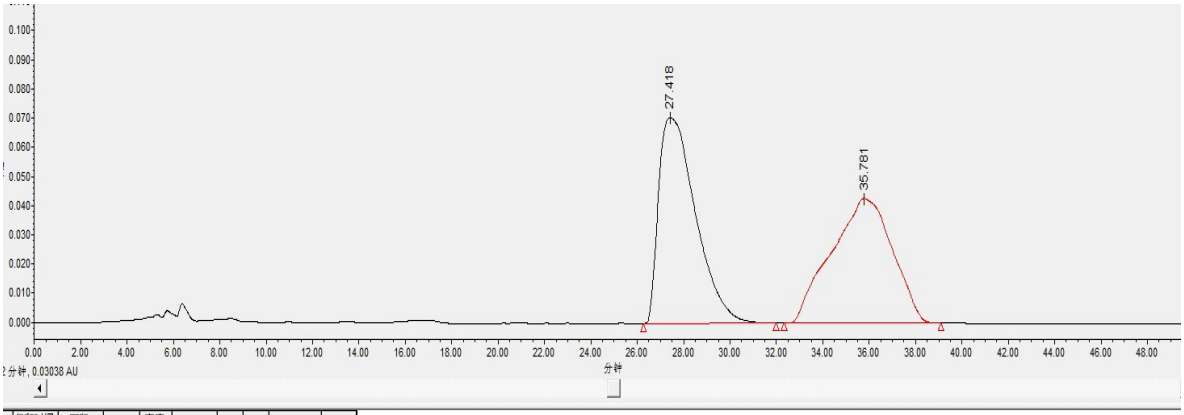
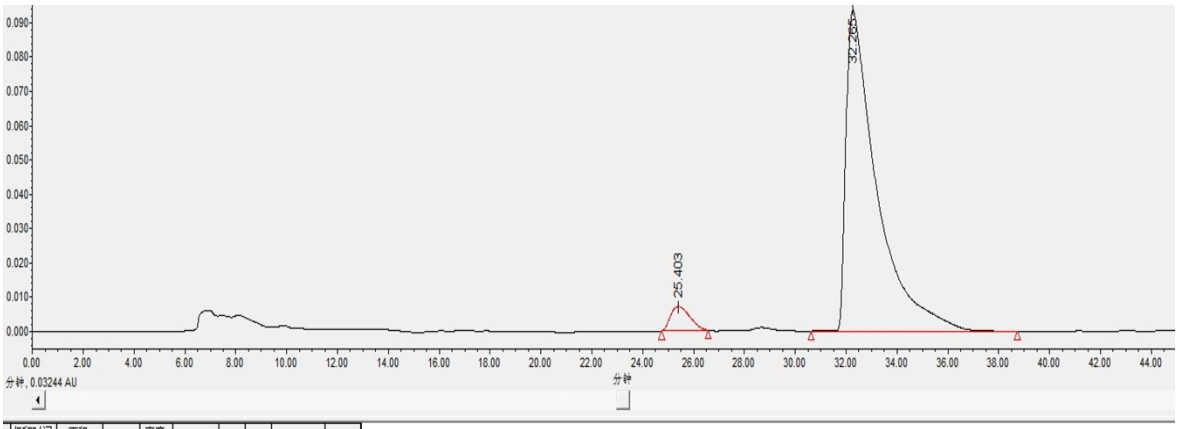


	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
	27.418	7807421	49.99	70506	bb			未知	
	35.781	7809503	50.01	42626	bb			未知	



	保留时间 (分钟)	面积 (微伏*秒)	% 面积	高度 (微伏)	积分类型	含量	单位	峰类型	峰代码
	25.403	372535	4.52	7055	bb			未知	
	32.265	7862047	95.48	93609	bb			未知	

S6 References

[1] X. Mei, C. Wolf, *J. Org. Chem.*, 2005, **70**, 2299.

[2] H. D. Gridev, C. Fan, P. G. Pringle, *Chem. Commun.*, 2007, 1319.

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