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硫脲衍生物有机催化蒽酮与硝基烯烃的不对称 Michael 加成反应

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摘要：将硫脲衍生物用于有机催化蒽酮和β-硝基烯烃的不对称 Michael 加成反应. 考察溶剂、温度及催化剂用量等对反应催化性能的影响. 结果表明，最佳催化条件为 5%(摩尔百分数)催化剂 **1f**，二氯甲烷为溶剂，室温反应. 得到了 80%~97%的化学产率和最高达 99%ee 的对映选择性.

关键词：硫脲衍生物；有机催化；不对称 Michael 加成反应；蒽酮；β-硝基烯烃
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Michael 加成反应是一种高效的构建 C—C 键的重要方法[1-3]. 近年来，有机小分子催化的不对称 Michael 反应引起了广泛关注[4-7]. 脲/硫脲衍生物由于具有很强的氢键活化能力，成功的实现了对多种反应的高对映选择性催化，尤其在各类底物的不对称 Michael 加成反应中取得了很大进展[8-25]. 然而，蒽酮化合物作为亲核试剂在不对称 Michael 加成反应的文献报道较少[26-30]. 2007 年，Shi 首次报道了金鸡纳碱有机催化的蒽酮与β-硝基烯烃的不对称 Michael 加成反应，得到了 80%~99%ee 的对映选择性[27]. 2009 年，Yuan 报道了叔胺硫脲类有机催化剂在该反应中的应用，得到了 60%~94%ee 的立体选择性[28]. 2010 年 He 报道了伯胺硫脲有机催化蒽酮不对称 Michael 加成反应，得到了 65%~86%的对映选择性[29]. 这里我们报道系列脲/硫脲催化剂 **1a-g** (Fig.1)有机催化蒽酮与β-硝基苯烯烃的不对称 Michael 加成反应，以期扩大该反应的催化剂类型.

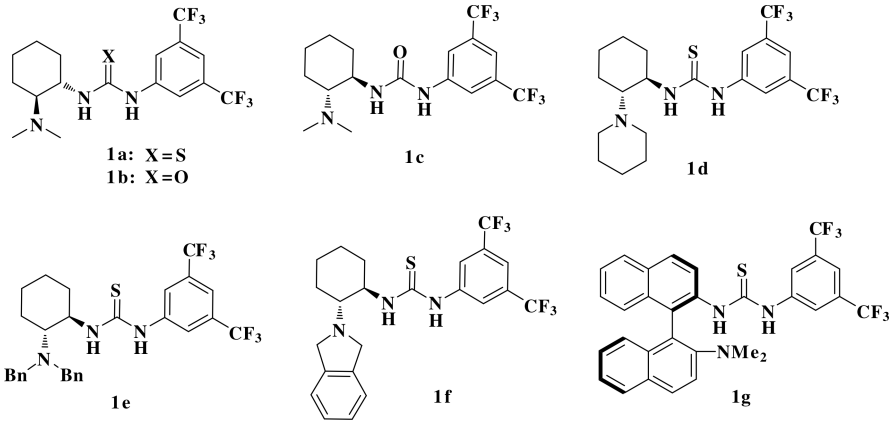

图 1 催化剂 **1a-g** 的结构

Fig.1 The structures of catalysts **1a-g**

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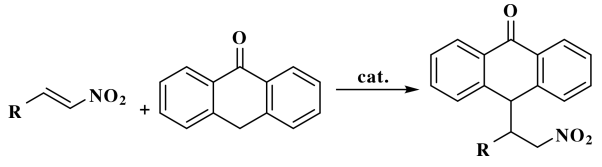
1 实验部分

1.1 试剂和仪器

Bruker Avance-500 型核磁共振谱仪(均以 $CDCl_3$为溶剂, TMS 为基准物质, 德国 Bruker 公司); MICROMASS Quattro Premier 型质谱仪(美国 waters 公司); LC-20A 高效液相色谱仪(日本岛津公司), Daicel Chiralpak AD-H, Chiralcel OD-H 手性色谱柱(日本大赛璐公司). 脲及硫脲衍生物为上海大赛璐药物手性技术(上海)有限公司产品, 其他试剂均为市售分析纯产品.

1.2 不对称 Michael 加成反应

于 5 mL 圆底烧瓶中依次加入反式硝基苯乙烯(29.8 mg, 0.2 mmol), 催化剂(0.01 mmol), 蒽酮(46.6 mg, 0.24 mmol), 二氯甲烷 3.0 mL, 室温搅拌反应 12~18 h, TLC 监测. 反应完毕后, 经硅胶柱层析分离, Hex∶EtOAc(9∶1)洗脱, 得到产品 **3a-m**.



10-(2-硝基-1-苯基乙基)-10*H*- 蒽-9-酮 **3a**: 白色固体; mp=145~147 ℃, [文献值[28] mp=146.8~149.0 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (d, *J* = 8.0 Hz, 1H), 7.98 (d, *J* = 8.0 Hz, 1H), 7.67-7.59 (m, 2H), 7.53-7.46 (m, 2H), 7.45-7.40 (m, 2H), 7.17-7.13 (m, 1H), 6.95 (t, *J* = 7.5 Hz, 2H), 6.05 (d, *J* = 8.0 Hz, 2H), 4.89 (dd, *J* = 9.0,13.0 Hz, 1H), 4.60 (dd, *J* = 7.0, 13.0 Hz, 1H), 4.55 (d, *J* = 3.5 Hz, 1H), 4.08-4.04 (m, 1H); HPLC (Daicel Chiralpak AD-H, V_{hex}∶$V_{i\,PrOH}$ = 97∶3, 0.6 mL/min, 254 nm), t_R: 45.9 min (major), 51.6 min (minor). $[\alpha]_D^{25}$ = + 23.9 (*c* = 0.50 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +25.4 (*c* = 0.48 in $CHCl_3$).

10-[1-(2-氟苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3b**: 白色固体; mp = 117~119 ℃; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.13 (d, *J* = 7.5 Hz, 1H), 8.07 (d, *J* = 7.5 Hz, 1H), 7.66-7.61 (m, 1H), 7.57-7.49 (m, 3H), 7.48-7.44 (m, 1H), 7.26-7.18 (m, 2H), 6.88-6.78 (m, 2H), 6.07 (t, *J* = 7.5 Hz, 1H), 4.74 (dd, *J* =8.0, 13.5 Hz, 1H), 4.60 (d, *J* = 9.0, 1H), 4.54 (dd, *J* = 8.0, 13.5 Hz, 1H), 4.39-4.35 (m, 1H); HPLC (Daicel Chiralpak AD-H, V_{hex}∶$V_{i\,PrOH}$ = 97∶3, 0.6 mL/min, 254 nm), t_R: 54.4 min (major), 64.1 min (minor). $[\alpha]_D^{25}$ = + 17.5 (*c* = 0.55 in $CHCl_3$).

10-[1-(2-氯苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3c**: 白色固体; mp = 123~124 ℃, [文献值[27] mp = 126.2~126.7 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.18 (d, *J* = 7.5 Hz, 1H), 8.15 (d, *J* = 7.5 Hz, 1H), 7.70-7.64 (m, 2H), 7.54-7.51 (m, 1H), 7.47-7.43 (m, 1H), 7.42-7.35 (m, 2H), 7.23-7.19 (m, 1H), 7.02 (t, *J* = 7.5 Hz, 1H), 6.80 (d, *J* = 7.0 Hz, 1H), 6.23 (d, *J* = 8.0 Hz, 1H), 4.72 (bs, 1H), 4.66 (d, *J* = 3.5 Hz, 1H), 4.44-4.38 (m, 2H); HPLC (Daicel Chiralpak AD-H, V_{hex}∶$V_{i\,PrOH}$ = 97∶3, 0.6 mL/min, 254 nm), t_R: 33.4 min (major), 53.9 min (minor). $[\alpha]_D^{25}$ = +18.6(*c* = 0.60 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +14.8 (*c* = 0.54 in $CHCl_3$).

10-[1-(2-溴苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3d**: 白色固体; mp = 100~102 ℃, [文献值[28] mp = 62.8~65.6 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.22-8.18 (m, 2H), 7.80 (bs, 1H), 7.71-7.68 (m, 1H), 7.61 (d, *J* = 6.5 Hz, 1H), 7.55 (t, *J* = 7.5 Hz, 1H), 7.49-7.45 (m, 1H), 7.38 (t, *J* = 7.5 Hz, 1H), 7.17-7.13 (m, 1H), 7.07 (t, *J* = 7.5 Hz, 1H), 6.72-6.71 (m, 1H), 6.25 (dd, *J* = 1.5, 8.0 Hz, 1H), 4.73 (bs, 1H), 4.72 (s, 1H), 4.36 (d, *J* = 6.0 Hz, 2H); HPLC (Daicel Chiralpak AD-H, V_{hex}∶$V_{i\,PrOH}$ = 97∶3, 0.6 mL/min, 254 nm), t_R: 42.3 min (major), 61.9 min (minor). $[\alpha]_D^{25}$ =+ 8.0 (*c* = 0.53 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +7.1 (*c* =0.74 in $CHCl_3$).

10-[1-(3-氟苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3e**: 白色固体; mp = 128~130 ℃, [文献值[28] mp = 123.8~126.9 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 (d, *J* = 7.5 Hz, 1H), 8.02 (d, *J* = 7.5 Hz, 1H), 7.69-7.59 (m, 2H), 7.55-7.40 (m, 4H), 6.98-6.82 (m, 2H), 5.88 (d, *J* = 7.5 Hz, 1H), 5.80-5.76 (m, 1H), 4.86 (dd, *J* = 8.5, 13.5 Hz, 1H), 4.59 (dd, *J* = 8.5, 13.5 Hz, 1H), 4.55 (d, *J* = 3.5 Hz, 1H), 4.08-4.02 (m, 1H); HPLC

(Daicel Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 97 : 3, 0.6 mL/min, 254 nm), t_R: 65.9 min (major), 71.9 min (minor). $[\alpha]_D^{25}$ = + 28.5 (c = 0.52 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +26.3 (c = 0.58 in $CHCl_3$).

10-[1-(3-溴苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3f**: 白色固体; mp = 120 ~ 121 ℃, [文献值[28] mp = 114.7 ~ 117.1 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (d, J = 7.5 Hz, 1H), 8.02 (d, J = 7.5 Hz, 1H), 7.69-7.60 (m, 2H), 7.56-7.41 (m, 4H), 7.27 (d, J = 9.0 Hz, 1H), 6.83 (t, J = 8.0 Hz, 1H), 6.14 (s, 1H), 6.01 (d, J = 7.5 Hz, 1H), 5.96 (d, J = 7.5 Hz, 1H), 4.85 (dd, J = 8.5, 13.5 Hz, 1H), 4.59-4.54 (m, 2H), 4.04-3.98 (m, 1H); HPLC (Daicel Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 97 : 3, 0.6 mL/min, 254 nm), t_R: 59.6 min (major), 73.7 min (minor). $[\alpha]_D^{25}$ = + 35.2 (c = 0.42 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +31.0 (c = 0.58 in $CHCl_3$).

10-[1-(3-甲基苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3g**: 白色固体; mp = 107 ~ 109 ℃, [文献值[28] mp = 111.5 ~ 113.9 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.06 (d, J = 8.0 Hz, 1H), 7.97 (d, J = 8.0 Hz, 1H), 7.66- 7.58 (m, 2H), 7.52-7.47 (m, 2H), 7.43-7.38 (m, 2H), 6.95 (d, J = 7.5 Hz, 1H), 6.82 (t, J = 7.5 Hz, 1H), 5.86 (d, J = 7.5 Hz, 1H), 5.77 (s, 1H), 4.85 (dd, J = 9.0, 13.0 Hz, 1H), 4.57 (dd, J = 7.0, 13.5 Hz, 1H), 4.52 (d, J = 3.5 Hz, 1H), 4.01-3.98 (m, 1H), 2.02 (s, 3H); HPLC (Daicel Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 97 : 3, 0.6 mL/min, 254 nm), t_R: 36.1 min (major), 53.0 min (minor). $[\alpha]_D^{25}$ = + 37.1 (c = 0.45 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +33.2 (c = 0.60 in $CHCl_3$).

10-[1-(4-氟苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3h**: 白色固体; mp = 165 ~ 167 ℃, [文献值[28] mp = 170.1 ~ 172.0 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (d, J = 7.5 Hz, 1H), 8.00 (d, J = 7.5 Hz, 1H), 7.67-7.60 (m, 2H), 7.53-7.42 (m, 4H), 6.64 (d, J = 7.5 Hz, 2H), 6.02-5.99 (m, 2H), 4.87 (dd, J = 9.0, 13.0 Hz, 1H), 4.59-4.52 (m, 2H), 4.06-4.02 (m, 1H); HPLC (Daicel Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 97 : 3, 0.6 mL/min, 254 nm), t_R: 53.3 min (major), 58.6 min (minor). $[\alpha]_D^{25}$ = +33.5 (c = 0.65 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +31.0 (c = 0.46 in $CHCl_3$).

10-[1-(4-氯苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3i**: 白色固体; mp = 170 ~ 172 ℃, [文献值[28] mp = 168.7 ~ 171.2 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (d, J = 8.0 Hz, 1H), 8.03 (d, J = 8.0 Hz, 1H), 7.68-7.59 (m, 2H), 7.54-7.44 (m, 3H), 7.40 (d, J = 7.5 Hz, 1H), 6.95 (d, J = 8.5 Hz, 2H), 6.02 (d, J = 8.0 Hz, 2H), 4.85 (dd, J = 8.5, 13.0 Hz, 1H), 4.57-4.52 (m, 2H), 4.06-4.02 (m, 1H); HPLC (Daicel Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 97 : 3, 0.6 mL/min, 254 nm), t_R: 41.9 min (major), 47.5 min (minor). $[\alpha]_D^{25}$ = + 24.3 (c = 0.50 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +21.7 (c = 0.40 in $CHCl_3$).

10-[1-(4-甲基苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3j**: 白色固体; mp = 158 ~ 160 ℃, [文献值[28] mp = 156.0 ~ 158.1 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (d, J = 7.5 Hz, 1H), 8.00 (d, J = 7.5 Hz, 1H), 7.67-7.58 (m, 2H), 7.53-7.49 (m, 2H), 7.45-7.38 (m, 2H), 6.76 (d, J = 8.0 Hz, 2H), 5.96 (d, J = 8.0 Hz, 2H), 4.84 (dd, J = 9.0, 13.0 Hz, 1H), 4.57-4.52 (m, 2H), 4.05-4.00 (m, 1H), 2.22 (s, 3H); HPLC (Daicel Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 97 : 3, 0.6 mL/min, 254 nm), t_R: 34.0 min (major), 36.3 min (minor). $[\alpha]_D^{25}$ = + 28.9 (c = 0.56 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +25.4 (c = 0.62 in $CHCl_3$).

10-[1-(4-硝基苯基)-2- 硝基乙基]-10*H*-蒽-9-酮 **3k**: 白色固体; mp = 189 ~ 191 ℃, [文献值[28] mp = 194.5 ~ 196.1 ℃]; ^{1}H NMR (500 MHz, $CDCl_3$) δ 9.90 (d, J = 7.5 Hz, 1H), 7.85-7.69 (m, 6H), 7.58-7.48 (m, 3H), 6.46 (d, J = 8.5 Hz, 2H), 5.47 (dd, J = 5.0, 13.5 Hz, 1H), 5.06 (dd, J = 10.0, 13.5 Hz, 1H), 4.95 (d, J = 4.0 Hz, 1H), 4.15-4.10 (m, 1H); HPLC (Chiralpak AD-H, V_{hex} : $V_{i\text{PrOH}}$ = 70 : 30, 1.0 mL/min, 254 nm), t_R: 12.7 min (major), 16.9 min (minor). $[\alpha]_D^{25}$ = + 25.1 (c = 0.55 in $CHCl_3$), 文献值[28] $[\alpha]_D^{20}$ = +21.2 (c = 0.42 in $CHCl_3$).

10-[1-(4-甲氧基苯基)-2- 硝基乙基]-10*H*-蒽-

9-酮 **3l**：白色固体；mp = 117~119 ℃，[文献值[28] mp = 119.8 ~ 122.7 ℃]；^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (d, *J* = 8.0 Hz, 1H), 7.99 (d, *J* = 7.5 Hz, 1H), 7.66-7.65 (m, 2H), 7. 50-7. 38 (m, 4H), 6.47 (d, *J* = 8.5 Hz, 2H), 5.95 (d, *J* = 8.5 Hz, 2H), 4.83 (dd, *J* = 9.0, 13.0 Hz, 1H), 4.55 (dd, *J* = 8.0, 13.0 Hz, 1H), 4.49 (d, *J* = 3.5 Hz, 1H), 4.03-3.97 (m, 1H), 3.68 (s, 3H)；HPLC (Chiralcel OD-H, V_{hex} ∶ $V_{i PrOH}$ = 70 ∶ 30, 1.0 mL/min, 254 nm), t_R: 21.5 min (major), 29.2 min (minor). $[\alpha]_D^{25}$ = +20.8 (*c* = 0.38 in $CHCl_3$)，文献值[28] $[\alpha]_D^{20}$ = +18.7 (*c* = 0.74 in $CHCl_3$).

10-[1-环己基-2-硝基乙基]-10*H*-蒽-9-酮 **3m**：白色固体；mp = 123~125 ℃，[文献值[28] mp = 127.3~130.8 ℃]；^{1}H NMR (500 MHz, $CDCl_3$) δ 8.30 (t, *J* = 8.5 Hz, 2H), 7.67-7.60 (m, 2H), 7.57-7.42 (m, 4H), 4.45 (dd, *J* = 9.0, 13.0 Hz, 1H), 4.35 (d, *J* = 2.5 Hz, 1H), 4.27 (dd, *J* = 5.0, 13.0 Hz, 1H), 2.73-2.65 (m, 1H), 1.62-1.48 (m, 2H), 1.44-1.35 (m, 2H), 1.20-1.02 (m, 3H), 0.97-0.75 (m, 2H), 0.45-0.25 (m, 2H)；HPLC (Chiralpak AD-H, V_{hex} ∶ $V_{i PrOH}$ = 80 ∶ 20, 1.0 mL/min, 254 nm), t_R: 8.9 min (major), 9.4 min (minor). $[\alpha]_D^{25}$ = +63.6 (*c* = 0.40 in $CHCl_3$)，文献值[28] $[\alpha]_D^{20}$ = +61.0 (*c* = 0.24 in $CHCl_3$).

2 结果与讨论

2.1 催化剂 1a-g 催化不对称 Michael 加成反应

将催化剂 **1a-g** 用于反式硝基苯乙烯与蒽酮的不对称 Michael 加成反应，以二氯甲烷为溶剂，室温反应，考察催化剂的催化性能，结果见表 1.

由表 1 反应结果可以得出以下结论：7 种(硫)脲类催化剂在二氯甲烷中均能顺利催化硝基苯乙烯与蒽酮的不对称 Michael 加成反应，得到 80%~92%的产率. 其中硫脲催化剂 **1f** 催化该反应得到了最好的对映选择性(85% ee, entry 6)，产品的构型，通过测定旋光值，对比文献报道[27]的旋光值确定主要产物的构型为 *S* 型.

2.2 反应条件的优化

将上述最好的催化剂 **1f** 用于硝基苯乙烯与蒽酮的不对称Michael加成反应中，考察溶剂、温度、催化剂用量等因素对反应立体选择性的影响，以期获得更好的催化剂体系. 结果见表 2.

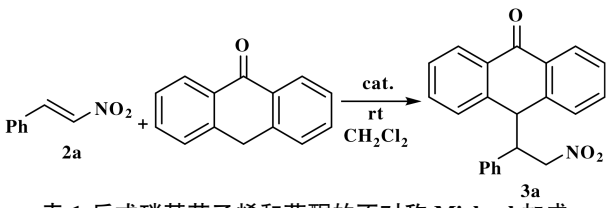


表 1 反式硝基苯乙烯和蒽酮的不对称 Michael 加成反应结果[a]

Table 1 Asymmetric Michael addition of nitrostyrene and anthrone[a]

Entry	Catalyst	Yield/%[b]	%ee[c]	Conf.[d]
1	**1a**	80	69	*R*
2	**1b**	92	61	*R*
3	**1c**	90	53	*S*
4	**1d**	87	65	*S*
5	**1e**	90	27	*S*
6	**1f**	89	85	*S*
7	**1g**	88	55	*S*

a. All of the reactions were performed with nitroalkenes 0.20 mmol, anthrone 0.24 mmol; b. Isolated yield; c. Determined by HPLC analysis (Chiralpak AD-H); d. The configuration was established by comparison with the optical rotation from the literature[27].

由表 2 结果可以看出：(1)溶剂对反应的立体选择性有显著影响，其中二氯甲烷和氯仿作为溶剂均得到了最好的 ee 值(entries 1,8). 考虑到氯仿溶剂的毒性大，选择二氯甲烷为溶剂；(2)降温对反应的立体选择性没有改善，反应温度由室温降至 0 ℃,反应的立体选择性明显降低(entry 11vs entry 1)；(3)催化剂的用量由 10%(摩尔百分数)增加至 20%或降至 5%，反应的对映体过量值均增加了 6%(entries 9,10 vs entry 1)，反应产率以 20%(摩尔百分数)用量时略高. 但是，考虑到催化剂用量越少，反应的成本越低，因此，选择 5%(摩尔百分数)的催化剂用量，以及延长反应时间来提高反应产率；(4)当反应溶剂量加倍，既反应体系稀释条件下，反应的产率和立体选择性都有所下降. 综上所述，筛选出的最佳催化剂体系为：5%(摩尔百分数)的催化剂 **1f**，二氯甲烷为溶剂，室温反应.

表 2 反式硝基苯乙烯与蒽酮的不对称 Michael 加成反应条件筛选[a]

Table 2 Screening of Reaction Conditions for the Asymmetric Michael Addition Reaction[a]

Entry	Solvent	Cat.ammount/(% mol)	Temp./℃	Yield/%[b]	/%ee[c]
1	CH_2Cl_2	10	rt	92	85
2	toluene	10	rt	80	71
3	CH_3CN	10	rt	75	41
4	$C_2H_4Cl_2$	10	rt	82	83
5	THF	10	rt	90	63
6	EA	10	rt	83	75
7	Et_2O	10	rt	85	67
8	$CHCl_3$	10	rt	93	85
9	**CH_2Cl_2**	**5**	**rt**	**92**	**91**
10	**CH_2Cl_2**	**20**	**rt**	**95**	**91**
11	CH_2Cl_2	10	0	85	55
12[d]	CH_2Cl_2	5	rt	87	82

a. All of the reactions were performed with nitroalkenes 0.20 mmol, anthrone 0.24 mmol; b. Isolated yield; c. Determined by HPLC analysis (Chiralpak AD-H); d. Solvent was double.

2.3 底物的扩展

将筛选出的催化条件应用于不同取代 β 硝基芳基乙烯的不对称 Michael 加成反应，考察催化剂体系的普适性，结果见表 3.

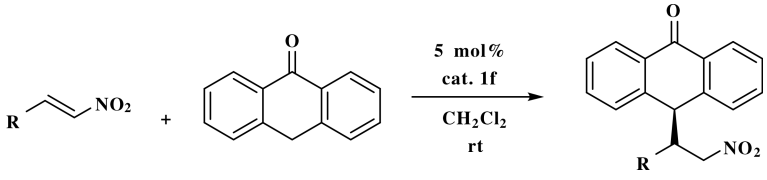


表 3 蒽酮和不同硝基烯烃的不对称 Michael 加成反应[a]

Table 3 Asymmetric Michael Addition Reactions of Anthrone to Various Nitroalkenes[a]

Entry	R	Product	Yield/%[b]	%ee[c]
1	Ph	**3a**	90	91
2	**2-F-Ph**	**3b**	**97**	**99**
3	2-Cl-Ph	**3c**	90	96
4	2-Br-Ph	**3d**	92	87
5	3-F-Ph	**3e**	92	94
6	3-Br-Ph	**3f**	93	88
7	**3-CH_3-Ph**	**3g**	**91**	**99**
8	4-F-Ph	**3h**	92	90
9	4-Cl-Ph	**3i**	91	95
10	4-CH_3-Ph	**3j**	95	91
11	4-NO_2-Ph	**3k**	90	87
12	4-OMe-Ph	**3l**	91	91
13	$c$$C_6H_{11}$-	**3m**	80	86

a. All of the reactions were performed with nitroalkenes 0.20 mmol, anthrone 0.24 mmol in toluene 3 mL; b. Isolated yield; c. Determined by HPLC (Chiralpak AD-H, Chiralcel OD-H).

实验结果表明：催化剂 **1f** 能够顺利地催化不同取代硝基乙烯为底物的反应，得到 80%～97%的产率. 并表现出优良的立体选择性(86%～99% ee)，其中以 2-氟及 3-甲基取代的底物获得了最高的对映体过量值(99%ee, entries 2, 7).

3 结论

我们将硫脲衍生物用于有机催化蒽酮与硝基烯烃的不对称 Michael 加成反应，筛选出最佳的催化体系，并将其应用于 13 种硝基烯烃和蒽酮的反应，均得到很好的化学产率和最高达 99%ee 的立体选择性. 催化剂体系对该反应表现出优秀的普适性.

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Thiourea Derivatives Organocatalyzed Asymmetric Michael Addition Reaction of Anthrone with Nitroalkenes

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Abstract: The (thio) urea derivatives as organocatalysts were applied in asymmetric Michael addition reaction of anthrone with different nitroalkenes. The effect of solvent, temperature and catalyst loading ammount were investigated. The optimized conditions were confirmed to include CH_2Cl_2 as the solvent with a 5% loading of catalyst **1f** at rt. The desired products were obtained in 80%~97% yield with up to 99%ee.

Key words: thiourea derivatives; organocatalysis; asymmetric Michael addition; anthrone; β-nitroalkenes

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