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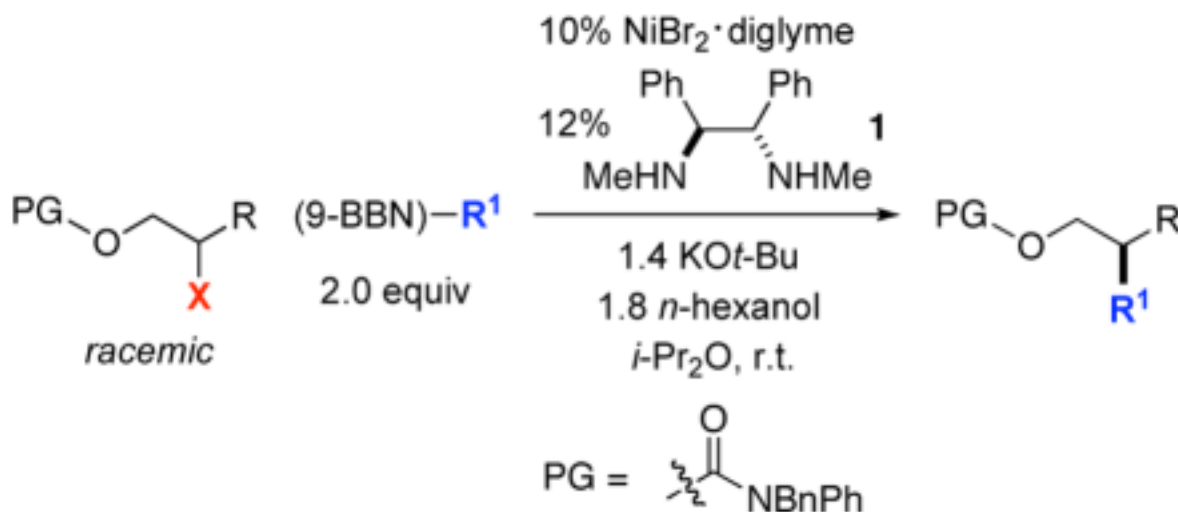
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Asymmetric Alkyl-Alkyl Cross-Couplings of Unactivated Secondary Alkyl Electrophiles: Stereoconvergent Suzuki Reactions of Racemic Acylated Halohydrins

Nathan A. Owston and Gregory C. Fu*

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Abstract



A method for asymmetric alkyl–alkyl Suzuki reactions of unactivated secondary alkyl electrophiles, specifically, cross-couplings of racemic acylated halohydrins with alkylborane reagents, has been developed. A range of protected bromohydrins, as well as a protected chlorohydrin and a homologated bromohydrin, are coupled in good ee by a catalyst derived from commercially available components.

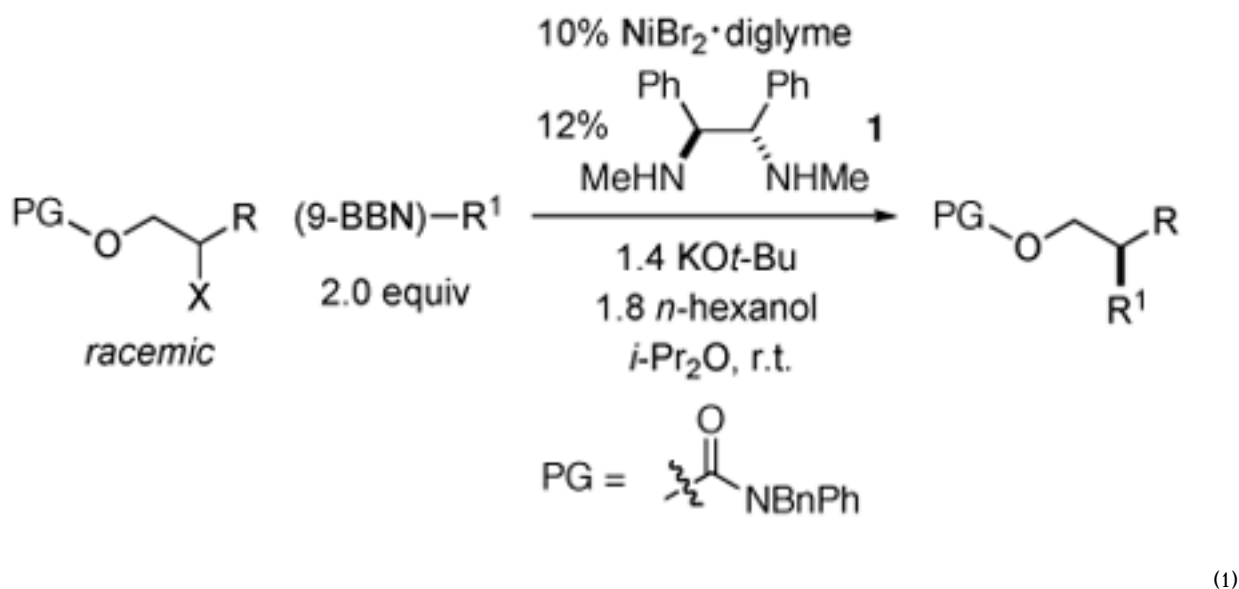
During the past several years, there have been substantial advances in the development of methods for metal-catalyzed cross-couplings of secondary alkyl electrophiles.¹ Furthermore, a number of catalytic enantioselective processes have been described; however, with one exception (homobenzylic bromides), this progress has been limited to couplings of *activated* electrophiles (e.g., α -halocarbonyl compounds, benzylic halides, allylic halides, and propargylic halides).^{2,3,4}

The ability to achieve asymmetric carbon–carbon bond formation with a wide range of *unactivated* halides would greatly enhance the utility of cross-couplings of alkyl electrophiles

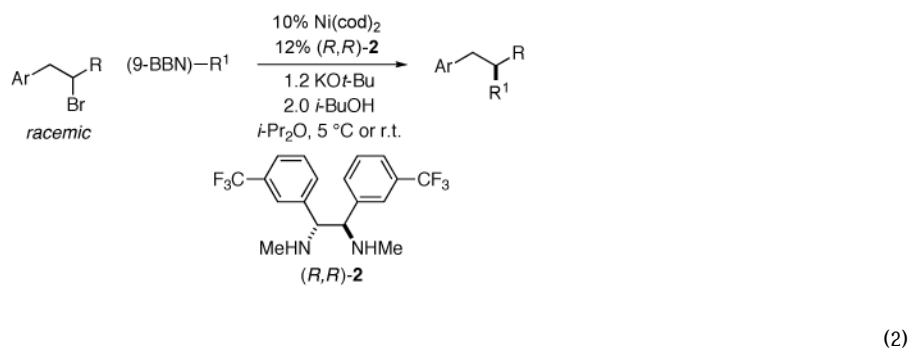
gcf@mit.edu.

 Supporting Information Available: Experimental procedures and compound characterization data (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

in organic synthesis. In this report, we describe a method for enantioselective Suzuki reactions⁵ of a new family of unactivated secondary alkyl electrophiles, acylated halohydrins (eq 1).



In 2008, we established that homobenzylic bromides serve as suitable substrates for nickel-catalyzed asymmetric Suzuki reactions, thereby furnishing the first examples of enantioselective cross-couplings of unactivated secondary alkyl electrophiles (eq 2).² Although this study provided proof-of-principle for such processes, homobenzylic halides are a relatively uncommon substructure in organic molecules. We were therefore intrigued by our observation that low enantioselectivity is obtained when an ether is present in the R substituent of the electrophile (eq 2: 40% ee for R = CH₂OBn, Ar = Ph, and R¹ = *n*-Hex). We speculated that this anomalous result might be a manifestation of coordination of the ether oxygen to the nickel catalyst.



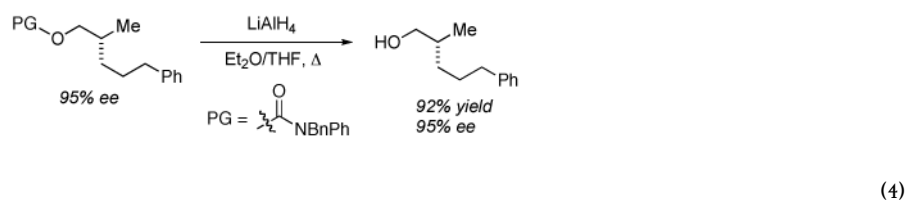
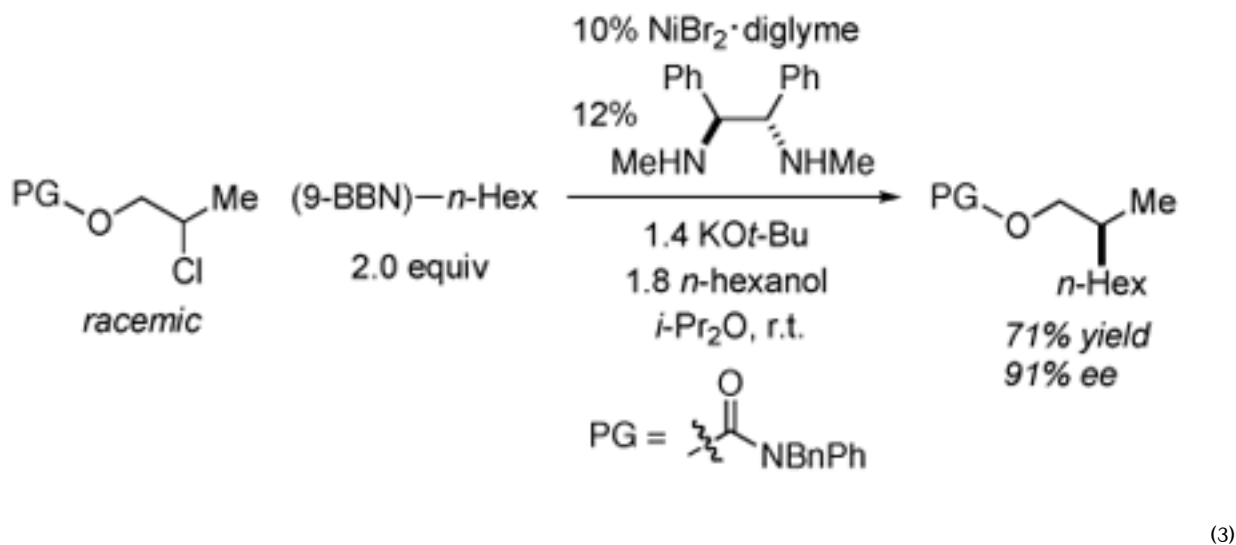
In view of the pervasiveness of oxygen-containing functional groups in organic molecules, we decided to pursue the possibility that this interaction could be exploited in the development of a method for the asymmetric cross-coupling of oxygenated, unactivated electrophiles. After a series of optimization studies, we determined that a racemic acylated bromohydrin can be coupled with an alkyloborane by a chiral nickel/diamine catalyst (both components are

commercially available and can be handled in air) in good ee and yield at room temperature (entry 1 of Table 1; 94% ee and 80% yield).

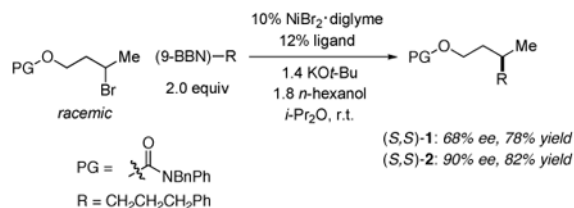
Table 1 provides information about the effect of a number of reaction parameters on the efficiency of this new stereoconvergent Suzuki reaction. In the absence of NiBr₂·diglyme, ligand **1**, or KO^t-Bu, essentially no cross-coupling is observed (entries 2–4). The conditions that were developed for asymmetric Suzuki couplings of homobenzylic bromides (eq 2) furnish only a small amount of product (18% yield; entry 5), due to the inferiority of Ni(cod)₂, ligand **2**, and *i*-BuOH, relative to NiBr₂·diglyme, ligand **1**, and *n*-hexanol (entries 6–8). TBME can be employed in place of *i*-Pr₂O as the solvent, at the expense of a slight erosion in ee (entry 9). Use of less alkylborane or catalyst results in a lower yield (entries 10 and 11). Other acyl protecting groups can be utilized, although there is a modest erosion in enantioselectivity and/or yield (entries 12–15).

We have examined the scope of this catalytic asymmetric alkyl–alkyl cross-coupling with respect to both the electrophilic and the nucleophilic partner (Table 2).⁶ In the case of the racemic electrophile, for R substituents that range in size from methyl to isobutyl, the Suzuki reaction proceeds with uniformly good ee (≥90% ee; entries 1–10). In addition, an array of alkylboranes serve as suitable nucleophiles, including substrates that bear a silyl ether (entry 3), an aryl alkyl ether (entry 4), an acetal (entry 6), and an aryl fluoride (entries 7 and 10).⁷

This new stereoconvergent method is effective for asymmetric alkyl–alkyl Suzuki reactions not only of racemic acylated bromohydrins, but also of chlorohydrins (eq 3); this represents the first example of an enantioselective cross-coupling of an unactivated secondary alkyl chloride. The carbamate protecting group can be cleaved in very good yield without eroding the ee (eq 4).



We have begun to investigate asymmetric Suzuki reactions of homologues of the acylated halohydrin electrophiles described above. In an initial study, we determined that, under the conditions optimized for bromohydrins, we obtain promising ee and yield for the cross-coupling of a racemic acylated homologue (eq 5).⁸ Importantly, simply by modifying the structure of the ligand, the desired stereoconvergent alkyl–alkyl Suzuki coupling can be accomplished with very good enantioselectivity (eq 5; ligand **2** is commercially available).



(5)

In summary, we have developed a method for asymmetric alkyl–alkyl Suzuki reactions of unactivated secondary alkyl electrophiles, specifically, cross-couplings of racemic acylated halohydrins with alkylborane reagents. A range of protected bromohydrins, as well as a protected chlorohydrin and a homologated bromohydrin, are coupled in good ee by a catalyst derived from commercially available components. This investigation is only the second report of an asymmetric cross-coupling of an unactivated secondary alkyl electrophile, and it represents an advance with respect to utility, enantioselectivity, and versatility. Additional efforts to develop useful new coupling reactions of alkyl electrophiles are underway.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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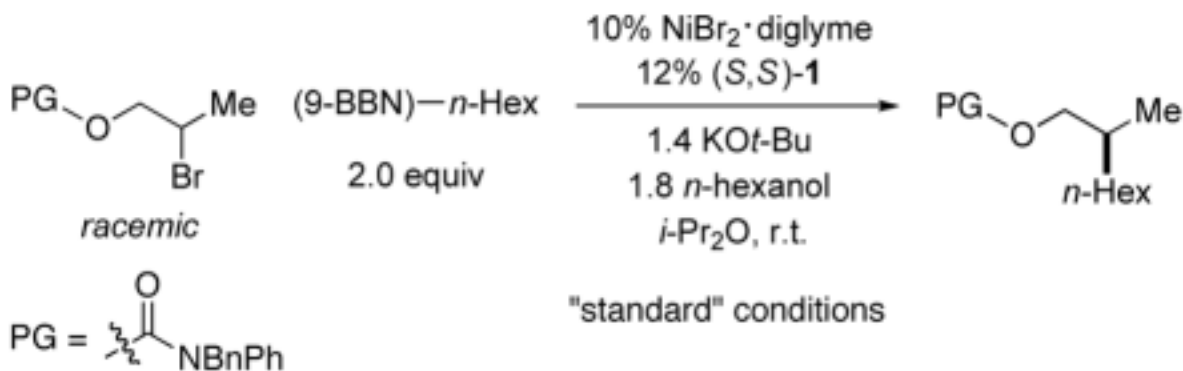
1. For leading references, see: Rudolph A, Lautens M. *Angew Chem, Int Ed* 2009;48:2656–2670.
2. For a report on catalytic asymmetric cross-couplings of unactivated secondary alkyl electrophiles, see: Saito B, Fu GC. *J Am Chem Soc* 2008;130:6694–6695. [PubMed: 18447357] (Suzuki alkylations of homobenzylic bromides).
3. For reports on catalytic asymmetric cross-couplings of activated secondary alkyl electrophiles, see: Negishi alkylations of α -bromoamides: (a) Fischer C, Fu GC. *J Am Chem Soc* 2005;127:4594–4595. [PubMed: 15796523] Negishi alkylations of 1-haloindanes: (b) Arp FO, Fu GC. *J Am Chem Soc* 2005;127:10482–10483. [PubMed: 16045323] Negishi alkylations of allylic chlorides: (c) Son S, Fu GC. *J Am Chem Soc* 2008;130:2756–2757. [PubMed: 18257579] Hiyama arylations and vinylations of α -bromoesters: (d) Dai X, Strotman NA, Fu GC. *J Am Chem Soc* 2008;130:3302–3303. [PubMed: 18302392] Negishi arylations of propargylic halides: (e) Smith SW, Fu GC. *J Am Chem Soc* 2008;130:12645–12647. [PubMed: 18763769] Couplings of alkynylindiums with benzylic bromides: (f) Cairo J, Perez Sestelo J, Sarandeses LA. *Chem Eur J* 2008;14:741–746. Negishi arylations of α -bromoketones: (g) Lundin PM, Esquivias J, Fu GC. *Angew Chem, Int Ed* 2009;48:154–156. Kumada arylations of α -bromoketones: (h) Lou S, Fu GC. *J Am Chem Soc* 2010;132:1264–1266. [PubMed: 20050651] Zirconium Negishi alkenylations of α -bromoketones: (i) Lou S, Fu GC. *J Am Chem Soc*

2010;132:5010–5011. [PubMed: 20302338] Suzuki arylations of α -haloamides: (j) Lundin PM, Fu GC. *J Am Chem Soc.* ASAP.

4. For overviews and leading references, see: Glorius F. *Angew Chem, Int Ed* 2008;47:8347–8349.(b) Reference 1.
5. The Suzuki reaction is perhaps the most widely used cross-coupling process. For leading references, see: (a) de Meijere, A.; Diederich, F., editors. *Metal-Catalyzed Cross-Coupling Reactions*. Wiley–VCH; New York: 2004. (b) Negishi, E-i, editor. *Handbook of Organopalladium Chemistry for Organic Synthesis*. Wiley Interscience; New York: 2002.
6. Notes: (a) During the course of a cross-coupling, no kinetic resolution of the secondary alkyl bromide is detected, and the ee of the product is constant. (b) On a gram-scale, the reaction illustrated in entry 1 of Table 2 proceeds in 95% ee and 76% yield. (c) In preliminary experiments under our standard conditions, an alkylboronic acid and a secondary alkyl-(9-BBN) reagent were not suitable cross-coupling partners, and the reaction of a hindered ($R = i\text{-Pr}$) and of an ether-containing ($R = \text{CH}_2\text{OMe}$) electrophile proceeded in good ee (>90%) but low yield (~30%) even in the presence of 15% $\text{NiBr}_2\cdot\text{diglyme}/18\%$ ligand 1. (d) Except in the case of entries 8 and 9 of Table 2 (20–30% recovered starting material; heating was not beneficial), little or no starting material remained when these cross-couplings were terminated. Hydrodebromination of the electrophile was observed as a side reaction. (e) For a proposed mechanism for Ni/terpyridine-catalyzed Negishi cross-couplings of unactivated alkyl electrophiles, see: Jones GD, Martin JL, McFarland C, Allen OR, Hall RE, Haley AD, Brandon RJ, Konovalova T, Desrochers PJ, Pulay P, Vicic DA. *J Am Chem Soc* 2006;128:13175–13183. [PubMed: 17017797] Lin X, Phillips DL. *J Org Chem* 2008;73:3680–3688. [PubMed: 18410144]
7. For examples of nickel-catalyzed cross-couplings of aryl fluorides, see: (a) Kiso Y, Tamao K, Kumada M. *J Organomet Chem* 1973;50:C12–C14. (b) Böhm VPW, Gstöttmayr CWK, Weskamp T, Herrmann WA. *Angew Chem, Int Ed* 2001;40:3387–3389. (c) Ackermann L, Born R, Spatz JH, Meyer D. *Angew Chem, Int Ed* 2005;44:7216–7219. (d) Yoshikai N, Mashima H, Nakamura E. *J Am Chem Soc* 2005;127:17978–17979. [PubMed: 16366529]
8. In contrast, in the case of the other example of an asymmetric cross-coupling of an unactivated secondary alkyl electrophile (Reference 2), the reaction of a homologue proceeded in low ee (14%).

Table 1

Asymmetric Alkyl–Alkyl Suzuki Reactions of Unactivated Alkyl Electrophiles: Racemic Acylated Bromohydrins



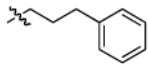
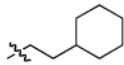
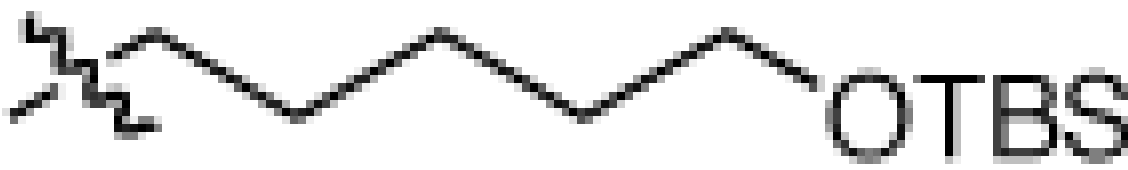
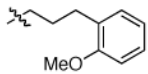

entry	variation from the "standard" conditions	ee (%)	yield (%) ^a
1	none	94	80
2	no NiBr ₂ · diglyme	–	<2
3	no (S,S)-1	–	<2
4	no KO ^t -Bu	–	<2
5	conditions in eq 2 (r.t.)	94	18
6	Ni(cod) ₂ , instead of NiBr ₂ · diglyme	94	38
7	(S,S)-2, instead of (S,S)-1	91	47
8	<i>i</i> -BuOH, instead of <i>n</i> -hexanol	95	67
9	TBME, instead of <i>i</i> -Pr ₂ O	90	79
10	1.5 equiv of alkylborane	94	61
11	5% NiBr ₂ · diglyme, 6% (S,S)-1	94	37
12	PG = CONEt ₂	87	66
13	PG = CONMePh	91	79
14	PG = CONPh ₂	95	71
15	PG = COAr (Ar = <i>p</i> -anisyl)	83	81

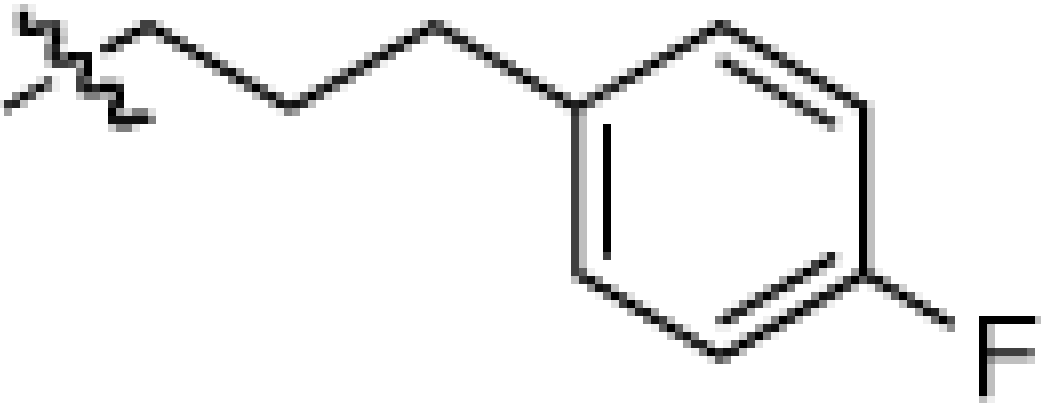
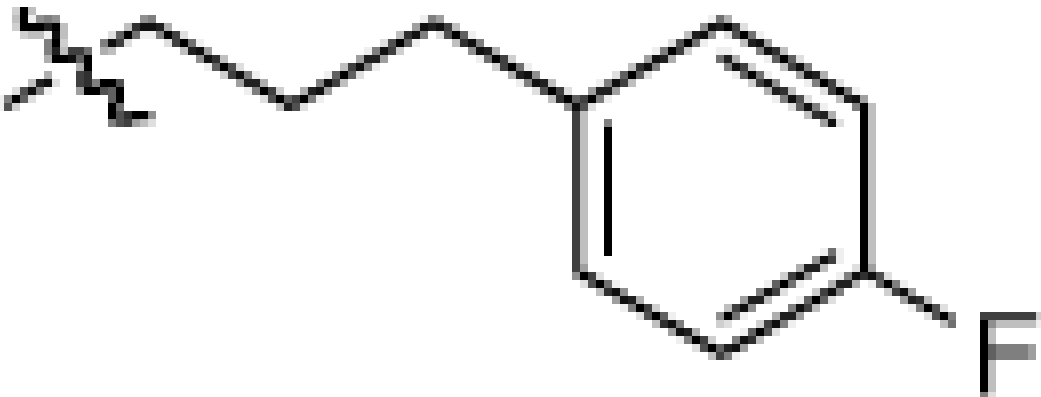
All data are the average of two experiments.

^aThe yield was determined by GC analysis versus a calibrated internal standard.

Table 2

Asymmetric Alkyl–Alkyl Suzuki Cross-Couplings of Racemic Acylated Bromohydrins: Scope (for the reaction conditions, see eq 1)

entry	R	R ¹	ee (%)
1	Me		94
2	Me		96
3	Me		94
4	Me		92
5	Et	<i>n</i> -Hex	96
6	Et		96

entry	R	R ¹	ee (%)
7	<i>n</i> -Hex		98
8 ^b	CH ₂ Ph	<i>n</i> -Hex	90
9 ^b	<i>i</i> -Bu	<i>n</i> -Hex	98
10	<i>i</i> -Bu		98

All data are the average of two experiments.

^aYield of purified product.

^b15% NiBr₂ · diglyme and 18% (*S,S*)-**1** were used.