Journal of Fluorine Chemistry 129 (2008) 1047–1051

Contents lists available at ScienceDirect

Journal of Fluorine Chemistry

journal homepage: www.elsevier.com/locate/fluor

Selective enhancement effects of silver salts on the transition metal-catalyzed synthesis of *gem*-difluorinated heterocyclics using 2,2-difluorohomopropargyl amides

Satoru Arimitsu, Rebecca L. Bottom, Gerald B. Hammond *

Department of Chemistry, University of Louisville, Louisville, KY 40292, USA

ARTICLE INFO

Article history:
Received 14 April 2008
Received in revised form 8 May 2008
Accepted 13 May 2008
Available online 20 May 2008

Keywords:
Pauson–Khand
Difluorolactam
Cyclization
Difluoropropargyl
Amide

ABSTRACT

The addition of silver salts had an effect on the catalyst activity in the Pd(0)-catalyzed cyclization-coupling tandem reaction, as well as in the Rh(I)-catalyzed Pauson–Khand reaction. The cationic palladium complex generated from $Pd(PPh_3)_4$ (2.5 mol%) with $AgSbF_6$ (1.5 equiv.) activates the triple bond of 2,2-difluoropropargylic amides to give the 4,5-disubstituted 3,3-difluoro-γ-lactams, through a sequential 5-*endo*-*dig* cyclization and cross-coupling reaction. The γ-lactam was transformed into ring-opened monofluorovinylic compounds after silica-gel chromatography. Pauson–Khand reaction of fluorinated 1,7-enyne amides using catalytic amounts of $[Rh(COD)_2]_2$ (5 mol%) and AgOTf (20 mol%) gave the corresponding *gem*-difluorinated bicyclic lactam.

1. Introduction

The juxtaposition of a carboxy amide – a common group present in pharmaceuticals and natural products [1] – and fluorine [2], is known to enhance the biological properties of the parent molecule. In the past decade, much effort has been spent on the synthesis of fluorinated carboxy amides. Conversely, α,α-difluorinated lactams are rare. Recently, we reported useful transformations toward the synthesis of fluorinated lactams (i.e. fluorinated isoquinolinones, fluorinated β- and γ-lactams) using a catalytic activation of triple bonds adjacent to a *gem*-difluoromethylene group [3]. These synthetic protocols may allow access to fluorinated drug-like compounds from readily available 2,2-difluoropropargylic amides (Scheme 1). As expected, fluorine withdraws electron density from the triple bond [4], making it less reactive toward electrophiles. In some cases, we have overcome this decreased reactivity utilizing higher temperatures as well as microwave irradiation, but these have caused thermal degradation of the product. An alternative solution is to activate the electrophile itself. In this paper, we report a selective enhancement caused by silver salts on the Pd(0)-catalyzed tandem cyclization-coupling reaction between organohalides and 2,2-difluoropropargylic amide **1**; and the Rh(I)-catalyzed Pauson–Khand reaction of fluorinated 1,7-enyne **7** (Scheme 2).

2. Results and discussion

2.1. Pd(0)-catalyzed tandem cyclization-coupling reaction of amide 1 with organohalides

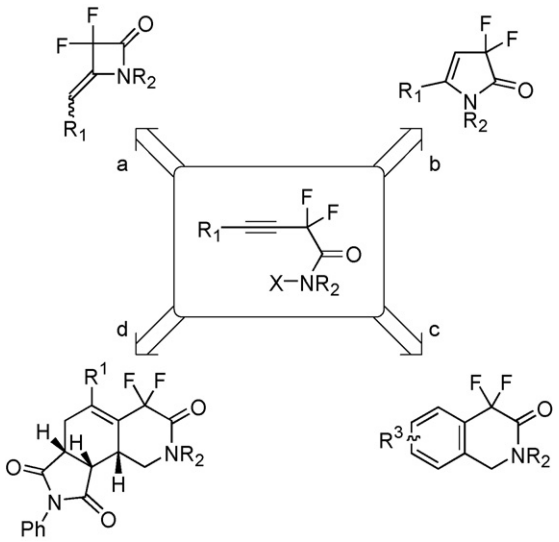
Tandem reactions are becoming increasingly popular in modern organic synthesis because of their atom-efficiency and fewer steps to afford final products compared to traditional chemistry [5]. We investigated the tandem Pd(0)-catalyzed cyclization-coupling reaction shown in Table 1. This reaction was highly influenced by silver salts (entries 1–6, Table 1). The use of $AgSbF_6$ (1.5 equiv.) suppressed the formation of by-product **4** [^{19}F NMR δ −112 ppm]. In this case, the ^{19}F NMR of the reaction mixture showed only the signal corresponding to product **3a** [^{19}F NMR δ −104 ppm] (entry 6, Table 1) [6]. Following purification by silica-gel chromatography, the ring-opened monofluorovinylic product **5a** [^{19}F NMR δ −116 ppm] was obtained in 40% yield (entry 6, Table 1).

Among the other bases examined, *t*-BuOK gave the best result. Based on ^{19}F NMR yields, DMF appeared to be the best solvent (entry 10, Table 1), but the isolated yield was lower because the impurities have a R_f similar to that of the desired product **5a**.

With electron-rich aryl iodides, the optimized reaction conditions led to decomposition (entries 1 and 2, Table 2). With an

* Corresponding author. Tel.: +1 502 852 5998; fax: +1 502 852 3899.
E-mail address: gb.hammond@louisville.edu (G.B. Hammond).

0022-1139/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jfluchem.2008.05.010



Scheme 1. Previously reported synthesis of α,α-difluorinated lactams. (a) $Pd(OAc)_2$ [X = H], (b) TBAF [X = H], (c) [2 + 2 + 2] cycloaddition [R_2 = Bn, X = H], (d) (i) enyne metathesis, (ii) Diels–Alder reaction [R_2 = Bn, X = allyl].

electron-deficient aryl iodide, such as 4-nitrophenyl iodide **2d**, the desired product **5d** was obtained, albeit in low yield (entry 3, Table 2). Replacement by allyl bromide **2e** resulted only in trace amounts of product, based on ^{19}F NMR data.

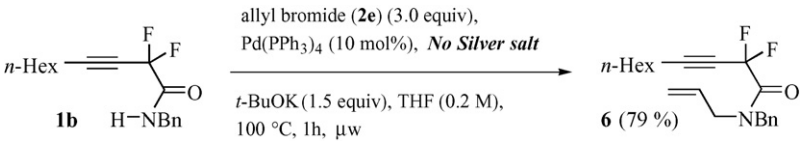
Interestingly, without $AgSbF_6$, the mixture of allyl bromide **2e** and amide **1b** furnished the C–N coupling product **6**, in good yield (Eq. (1)) [7].

The postulated reaction mechanism is depicted in Scheme 3. Silver salts can generate the cationic palladium complex after an oxidative addition of palladium to organohalides [8], thus coordinating more strongly with a triple bond and inducing a 5-*endo-dig* cyclization. Reductive elimination gives the final coupling product **3**. The intrinsic leaving ability of fluorine brings about the formation of an iminium intermediate [9] that can easily react with water to yield a hemiaminal, leading to the formation of **5**.

2.2. Rh(I)-catalyzed Pauson–Khand reaction of fluorinated 1,7-dienyne 7

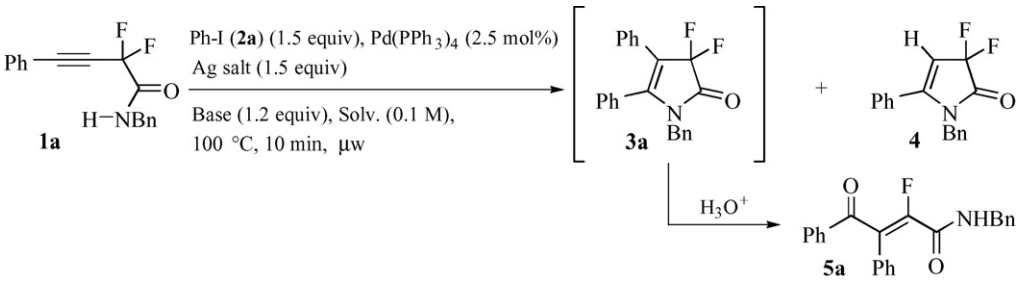
Although there are several publications that report the Pauson–Khand reaction of fluorinated building blocks, most utilize stoichiometric amounts of $Co_2(CO)_8$ [10], and none of them have reported a catalytic version [11]. The results of our study of the Rh(I)-catalyzed Pauson–Khand reaction are summarized in Table 3. Under standard reaction conditions no reaction was observed (entry 1, Table 3). Instead, we noticed that this reaction was very sensitive to several experimental parameters (e.g., catalyst, solvent, concentration, silver salt, and temperature) as described below.

The addition of AgOTf had a crucial effect on the activation of the rhodium catalyst (compare entries 1 and 2, Table 3) [12]. Other silver salts did not have this effect (entries 10–13, Table 3) [13]. The choice of solvent and concentration was also important to prevent the formation of by-products (mainly the dimer of **8**). Our best conditions produced **8** in 43% isolated yield (entry 5, Table 3). Utilizing cinnamaldehyde as a CO source did not give the desired product. Unfortunately, this reaction has strict limitations on the range of alkynes that can be utilized; for example, no reaction was observed with a phenyl-substituted alkyne.



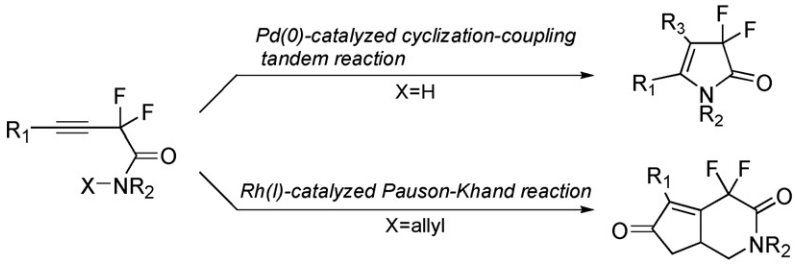
(1)

Table 1
Screening of Pd(0)-catalyzed tandem reaction of amide **1a** with iodobenzene **2a**



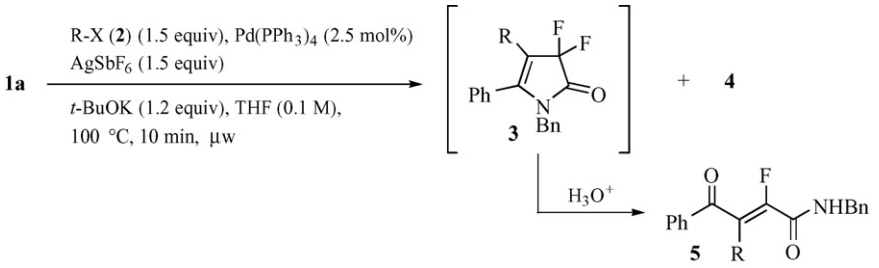
Entry	Base	Ag salt	Solvent	Yields of **3a**/**4**/**5a** (%)[a]
1	*t*-BuOK	–	THF	0/52/0
2	*t*-BuOK	$AgNO_3$	THF	0/50/0
3	*t*-BuOK	$AgClO_4$	THF	24/4/0
4	*t*-BuOK	AgOTf	THF	No rxn
5	*t*-BuOK	$AgBF_4$	THF	0/5/0
6	*t*-BuOK	$AgSbF_6$	THF	62/0/0 (40)
7	Na_2CO_3	$AgSbF_6$	THF	14/0/19
8	K_2CO_3	$AgSbF_6$	THF	33/0/0
9	NaOEt	$AgSbF_6$	THF	25/0/0
10	*t*-BuOK	$AgSbF_6$	DMF	56/0/0 (33)
11	*t*-BuOK	$AgSbF_6$	PhMe	21/3/0

[a] Yields were determined by ^{19}F NMR; values in parentheses correspond to isolated yield of **5a**.



Scheme 2. Possible new synthetic routes to fluorinated heterocyclics.

Table 2
Synthetic limitations of the Pd(0)-catalyzed tandem reaction



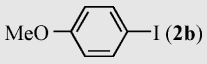
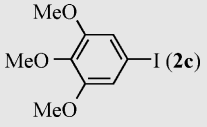
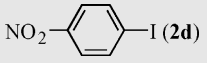
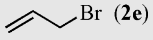
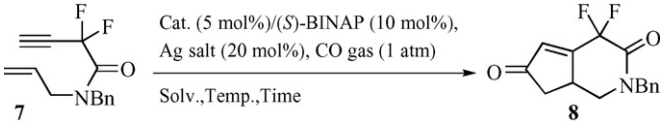
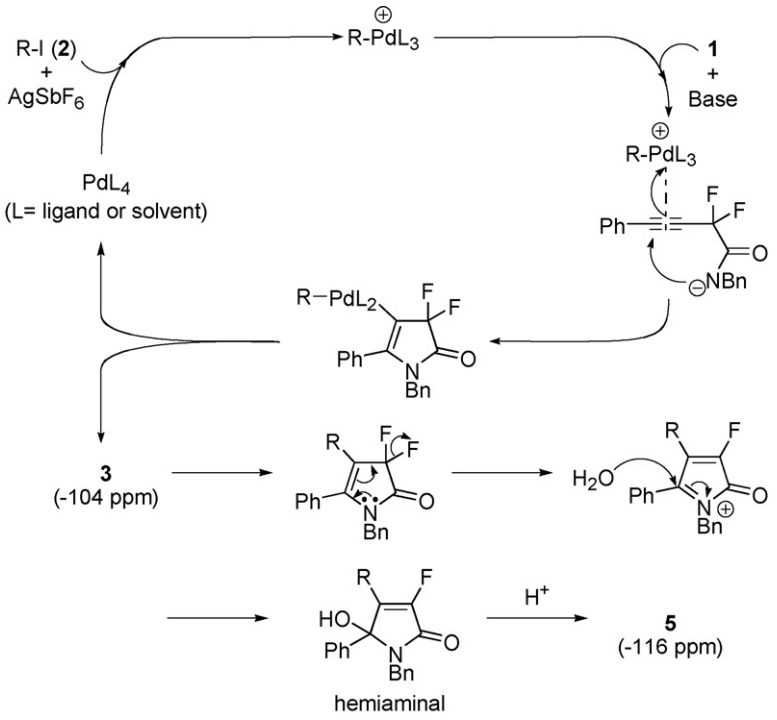
Entry	R-X	Isolate yields of **5** (%)
1		Decompo. (**5b**)
2		Decompo. (**5c**)
3		31 (**5d**)
4		Trace (**5e**)

Table 3
Screening of Rh(I)-catalyzed Pauson–Khand reaction



Entry	Catalyst	Ag salt	Solvent (X M)	Temperature	Time[a] (h)	Isolate yields of **8** (%)
1	$[Rh(COD)Cl]_2$[b]	–	THF (0.1)	70	24	No rxn
2	$[Rh(COD)Cl]_2$	AgOTf	THF (0.1)	70	1	22
3	$[Rh(COD)Cl]_2$	AgOTf	THF (0.1)	r.t.	15	No rxn
4	$[Ir(COD)Cl]_2$	AgOTf	THF (0.1)	70	15	No rxn
5	$[Rh(COD)Cl]_2$	AgOTf	THF (0.02)	70	6	43
6	$[Rh(COD)Cl]_2$	AgOTf	1,4-Dioxane (0.02)	70	6	No rxn
7	$[Rh(COD)Cl]_2$	AgOTf	DMF (0.02)	70	6	No rxn
8	$[Rh(COD)Cl]_2$	AgOTf	PhMe (0.02)	70	6	No rxn
9	$[Rh(COD)Cl]_2$	AgOTf	1,2-DCE[c] (0.02)	70	6	Trace
10	$[Rh(COD)Cl]_2$	$AgSbF_6$	THF (0.02)	70	6	Trace
11	$[Rh(COD)Cl]_2$	$AgBF_4$	THF (0.02)	70	6	Trace
12	$[Rh(COD)Cl]_2$	$AgClO_4$	THF (0.02)	70	6	Trace
13	$[Rh(COD)Cl]_2$	$AgNO_3$	THF (0.02)	70	6	No rxn

[a] The reaction progress was monitored by TLC and/or GC–MS.
[b] COD = 1,5-cyclooctadiene.
[c] 1,2-Dichloroethane.



Scheme 3. Proposed mechanism for the Pd(0)-catalyzed tandem reaction of **1** with **2**.

3. Conclusion

The addition of silver salts was investigated in the Pd(0)-catalyzed cyclization-coupling tandem reaction and in the Rh(I)-catalyzed Pauson–Khand reaction. Both cationic transition metal complexes activate the triple bond of 2,2-difluoropropargylamide. In both cases there are limitations on the scope of substrates that can be utilized. These reactions underscored the unique electronic properties of electron-deficient triple bonds and insinuate promising protocols that could turn unreactive triple bonds into useful synthetic handles.

4. Experimental

4.1. General

^{1}H, ^{13}C and ^{19}F NMR spectra were recorded at 500, 126 and 470 MHz respectively, using $CDCl_3$ as a solvent. The chemical shifts are reported in ^{TM} (ppm) values relative to $CHCl_3$ (δ 7.26 ppm for ^{1}H NMR and δ 77.0 ppm for ^{13}C NMR) and $CFCl_3$ (δ 0 ppm for ^{19}F NMR). Coupling constants are reported in hertz (Hz). All air and/or moisture sensitive reactions were carried out under argon atmosphere. Solvents (tetrahydrofuran, DMF) were dried using a commercial purification system. Toluene and 1,2-dichloroethane were distilled over CaH_2, and 1,4-dioxane was distilled over benzophenone/Na. All other commercial reagents were obtained from major chemical suppliers and used without further purification. ^{19}F NMR yield in the mixture was obtained using α,α,α-trifluoromethylbenzene as the internal reference.

4.2. General procedure of Pd(0)-catalyzed tandem cyclization-coupling reaction of amide 1a with organohalide 2

An oven-dried microwave vial (10 mL size) equipped with a stir bar, under argon atmosphere, was charged with *t*-BuOK (0.38 mmol, 1.2 equiv.), $Pd(PPh_3)_4$ (0.008 mmol, 2.5 mol%), $AgSbF_6$ (0.48 mmol, 1.5 equiv.) and fluorinated amide **1a** (0.32 mmol) into which phenyl iodide (0.48 mmol, 1.5 equiv.) in THF (3.2 mL, 0.1 M) was added via syringe. The vial was then placed in a CEM Discover microwave synthesizer at 100 °C for 10 min (at 150 W, 250 psi max); the temperature was monitored by computer during the reaction. After cooling to room temperature, the reaction was quenched with aqueous NH_4Cl (50 mL, 1/1 = water/saturated aqueous NH_4Cl). The mixture was extracted with ethyl acetate and the combined organic extracts were washed with brine and dried over anhydrous $MgSO_4$. ^{19}F NMR yield of the desired product **3a** was obtained after the removal of solvents. The final compound was isolated by silica-gel column chromatography eluted with hexane/ethyl acetate (5/1) yielding **5a** (0.051 mg, 40%) as a pale yellow solid.

4.2.1. 2-Fluoro-4-oxo-3,4-diphenyl-but-2-enoic acid benzylamide (5a)

mp 86–89 °C; ^{1}H NMR ($CDCl_3$) δ: 4.52 (s) and 4.53 (s) for 2H, 6.73 (bs, 1H), 7.13 (s, 1H), 7.19 (s, 1H), 7.24–7.30 (m, 8H), 7.30 (t, J = 7.5 Hz, 2H), 7.54 (t, J = 7.5 Hz, 1H), 7.90 (d, J = 7.0 Hz, 2H); ^{19}F NMR ($CDCl_3$) δ: −116.08 (s) and −116.15 (s) for 1F; ^{13}C NMR ($CDCl_3$) δ: 43.8 108.57, 108.60, 125.9, 127.1, 127.8, 127.9, 128.1, 128.6, 128.7, 128.8, 133.8, 136.8, 136.9, 155.4 (d, J = 295.3 Hz), 158.9 (d, J = 29.8 Hz), 187.9; IR (CCl_4) cm^{-1}: 3346, 3314, 3965, 3032, 2925, 2387, 2317, 1666, 1527, 1282.

4.2.2. 2-Fluoro-3-(4-nitrophenyl)-4-oxo-4-phenyl-but-2-enoic acid benzylamide (5d)

Viscous oil; ^{1}H NMR ($CDCl_3$) δ: 4.49 (s) and 4.50 (s) for 2H, 6.81 (bs, 1H), 7.08 (bs, 2H), 7.18–7.13 (m, 7H), 7.42 (t, J = 7.5 Hz, 2H), 7.53 (t, J = 7.5 Hz, 1H), 7.89 (d, J = 8.0 Hz, 2H); ^{19}F NMR ($CDCl_3$) δ: −115.8 (s) and −115.9 (s) for 1F; ^{13}C NMR ($CDCl_3$) δ: 43.9, 108.7 (d, J = 2.8 Hz), 121.4, 123.6, 125.9, 127.9, 128.3, 128.7, 128.8, 128.9, 133.9, 136.7, 136.9, 155.4 (d, J = 295.3 Hz), 158.9 (d, J = 29.8 Hz), 188.0; IR (CCl_4) cm^{-1}: 3321, 3063, 3033, 2928, 2352, 2319, 1715, 1661, 1521, 1448, 1277.

4.3. General procedure for the Pd(0)-catalyzed allyl-N coupling of fluorinated amide **1b**

An oven-dried microwave vial (10 mL size) equipped with a stir bar, under argon atmosphere, was charged with *t*-BuOK (0.66 mmol, 1.5 equiv.), $Pd(PPh_3)_4$ (0.044 mmol, 10 mol%) and fluorinated amide **1b** (0.44 mmol). Allyl bromide (1.32 mmol, 3.0 equiv.) in THF (2.2 mL, 0.2 M) was added via syringe. The vial was then placed in a CEM Discover microwave synthesizer at 100 °C for 1 h (at 150 W, 250 psi max); the temperature was monitored by computer during the reaction. After cooling to room temperature, the reaction was quenched with aqueous NH_4Cl (50 mL, 1/1 = water/saturated aqueous NH_4Cl). The mixture was extracted with ethyl acetate and the combined organic extracts were washed with brine and dried over anhydrous $MgSO_4$. After the removal of solvents, the final compound was isolated by silica-gel column chromatography eluted with hexane/ethyl acetate (40/1) to furnish **6** (0.116 mg, 79%) as a pale yellow liquid [14].

4.3.1. N-Allyl-N-benzyl-2,2-difluoro-4-phenyl-3-butynamide (6)

Oil; ^{1}H NMR ($CDCl_3$) δ: 0.89 (t, J = 6.5 Hz, 3H), 1.24–1.58 (m, 8H), 2.17–2.21 (m, 1H), 2.31–2.35 (m, 1H), 3.93 (d, J = 5.5 Hz) and 4.05 (d, J = 5.0 Hz) for 2H, 4.63 (s) and 4.76 (s) for 2H, 5.11 (d, J = 17.0 Hz) and 5.22 (d, J = 17.0 Hz) for 1H, 5.21 (d, J = 10.0 Hz) and 5.30 (d, J = 10.0 Hz) for 1H, 5.71–5.83 (m, 1H), 7.23–7.39 (m, 5H); ^{19}F NMR ($CDCl_3$) δ: −83.98 (s) and −84.68 (s) for 2F; ^{13}C NMR ($CDCl_3$) δ: 13.9, 18.5, 22.4, 27.4, 28.4, 31.1, 47.8, 48.0, 49.1, 50.1, 71.4 (t, J = 37.9 Hz), 71.5 (t, J = 37.7 Hz), 93.6 (t, J = 6.0 Hz), 93.8 (t, J = 6.0 Hz), 105.9 (t, J = 240.2 Hz), 106.1 (t, J = 240.9 Hz), 118.2, 119.1, 127.2, 127.6, 127.8, 128.0, 128.66, 128.69, 131.1, 132.3, 135.4, 136.0, 161.4 (t, J = 28.4 Hz), 161.6 (t, J = 28.3 Hz); IR (neat) cm^{-1}: 2931, 2861, 2250, 1686, 1444, 1222, 1072; MS m/z (%): 334 (100, M^++H), 276 (12), 91 (65); HRMS (FAB) calcd. for $C_{20}H_{25}F_2NO$ (M^+): 333.1904, found: 334.1989 (M^++H).

4.4. General procedure for the Rh(I)-catalyzed Pauson–Khand reaction of fluorinated 1,7-dienyne 7

An oven-dried two-necked round bottom flask (50-mL size) equipped with a condenser was loaded with (*S*)-BINAP (0.03 mmol, 10 mol%), $[Rh(COD)_2]_2$ (0.015 mmol, 5 mol%) and THF (2 mL) under argon; then the argon was replaced by carbon monoxide in a plastic balloon, and the whole reaction mixture was stirred for 30 min at 40 °C. AgOTf (0.06 mmol, 20 mol%) was added into the reaction mixture and stirred for another 30 min at 40 °C. After the fluorinated 1,7-dienyne **7** (0.3 mmol) was added with the aid of THF (13 mL, 0.2 M as a total concentration), the reaction mixture was stirred at 70 °C for additional 6 h. The organic solvent was removed from the resulting solution and the residue was charged on silica-gel column chromatography using hexane/Et_2O (1/3) as eluent to afford **8** (0.133 mg, 43%). The enantiomeric excess of the product **8** was not determined.

4.4.1. 2-Benzyl-4,4-difluoro-1,2,7,7a-tetrahydro-4H-[2]pyrindine-3,6-dione (8)

Oil; ^{1}H NMR ($CDCl_3$) δ: 2.07 (d, J = 19.0 Hz, 1H), 2.63 (dd, J = 6.5, 20.0 Hz, 1H), 2.93 (dt, J = 2.5, 11.5 Hz, 1H), 3.33–3.38 (m, 1H), 3.55 (dd, J = 7.0, 11.5 Hz, 1H), 4.45 (d, J = 14.5 Hz, 1H), 4.73 (d, J = 14.5 Hz, 1H), 6.44 (bs, 1H), 7.18–7.20 (m, 2H), 7.26–7.31 (m, 3H); ^{19}F NMR ($CDCl_3$) δ: −92.8 (d, J = 304.0 Hz, 1F), −116.3 (d, J = 300.7 Hz, 1F); ^{13}C NMR ($CDCl_3$) δ: 36.0 (d, J = 4.7 Hz), 38.9, 51.0, 51.8, 107.0 (dd, J = 237.7, 250.1 Hz), 128.27, 128.35, 129.1, 131.0, 134.8, 160.6 (t, J = 29.6 Hz), 165.6 (dd, J = 22.1, 24.9 Hz), 204.4; IR (CCl_4) cm^{-1}: 3432, 3356, 3087, 3032, 2919, 2850, 1959, 1722, 1680, 1451, 1066; MS m/z (%): 227 (34, M^+), 260 (15), 156 (9), 133 (11), 91 (100).

Acknowledgement

The authors are grateful to the National Science Foundation (CHE-0513483) for its financial support.

References

[1] A.K. Ghose, V.N. Viswanadhan, J.J. Wendoloski, J. Comb. Chem. 1 (1999) 55–68.
[2] For general reviews, see:
(a) K. Uneyama, Organofluorine Chemistry, Blackwell, Oxford, 2006;
(b) R.D. Chambers, Fluorine in Organic Chemistry, Blackwell, Oxford, 2004;
(c) P. Kirsch, Modern Fluoroorganic Chemistry, Wiley–VCH, Weinheim, 2004;
(d) B. Koksch, N. Sewald, H.-D. Jakubke, K. Burger, in: I. Ojima, J.R. McCarthy, J.T. Welch (Eds.), Biomedical Frontiers of Fluorine Chemistry, American Chemical Society, Washington, DC, 1996.
[3] (a) S. Fustero, B. Fernández, P. Bello, C. del Pozo, S. Arimitsu, G.B. Hammond, Org. Lett. 9 (2007) 4251–4253;
(b) S. Arimitsu, B. Fernández, C. del Pozo, S. Fustero, G.B. Hammond, J. Org. Chem. 73 (2008) 2656–2661.
[4] S. Arimitsu, G.B. Hammond, J. Org. Chem. 72 (2007) 8559–8561.
[5] Review for tandem reaction, see:
J.-C. Wasilke, S.J. Obrey, R.T. Baker, G.C. Bazan, Chem. Rev. 105 (2005) 1001–1020;
Example of transition metal catalyzed cyclization-coupling reactions, see:
(a) G. Balme, D. Bouyssi, T. Lomberget, N. Monteiro, Synthesis 14 (2003) 2115–2134;
(b) G. Battistuzzi, S. Cacchi, G. Fabrizi, Eur. J. Org. Chem. (2002) 2671–2681.
[6] Product 4a has been reported. See Ref. [3a]
[7] (a) J. Yin, S.L. Buchwald, Org. Lett. 2 (2000) 1101–1104;
(b) S.E. Byström, R. Aslanian, J.-E. Bäckvall, Tetrahedron Lett. 26 (1985) 1749–1752.
[8] (a) Y. Hu, Y. Zhang, Z. Yang, R. Fathi, J. Org. Chem. 67 (2002) 2365–2386;
(b) G. Zou, Y.K. Reddy, J.R. Falck, Tetrahedron Lett. 42 (2001) 7213–7215 (and references therein).
[9] For a similar example, see:
Y. Wang, S. Zhu, Org. Lett. 5 (2003) 745–748.
[10] (a) R. Nadano, J. Ichikawa, J. Chem. Lett. 36 (2007) 22–23;
(b) S. Harthong, T. Billard, B.R. Langlois, Synthesis 13 (2005) 2253–2263;
(c) A. Ferry, T. Billard, B.R. Langlois, Synlett 6 (2005) 1027–1029;
(d) M. Ishizaki, D. Suzuki, O. Hoshino, J. Fluorine Chem. 111 (2001) 81–90.
[11] For examples of Rh(I)-catalyzed Pauson–Khand reaction see:
(a) K. Fuji, T. Morimoto, K. Tsutsumi, K. Kakiuchi, Angew. Chem. Int. Ed. 42 (2003) 2409–2411;
(b) N. Jeong, B.K. Sung, Y.K. Choi, J. Am. Chem. Soc. 122 (2000) 6771–6772 (and references cited therein).
[12] Silver salts have been reported to enhance Rh(I)-catalyzed (e.g. $[Rh(CO)_2Cl]_2$, $[RhCl(CO_2)]_2$) Pauson–Khand reaction, see:
(a) K.M. Brummond, B. Mitasev, Org. Lett. 6 (2004) 2245–2248;
(b) Ref. [11b]..
[13] T. Shibata, N. Toshida, K. Takagi, J. Org. Chem. 67 (2002) 7446–7450 (and references cited therein).
[14] Product **6** has been reported. See Ref. [3b]