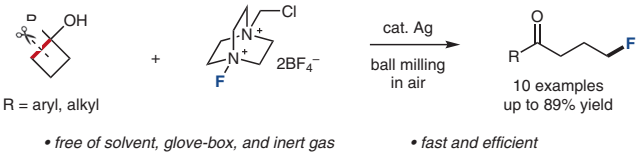
Synlett R. Isshiki et al. Cluster

Solid-State Silver-Catalyzed Ring-Opening Fluorination of Cyclobutanols by Using Mechanochemistry

Ryota Isshiki[*a,b]
Koji Kubota[*a,b]
Hajime Ito[*a,b]

[a] Institute for Chemical Reaction Design and Discovery (WPI-ICReDD), Hokkaido University, Sapporo, Hokkaido 060-8628, Japan
isshiki@icredd.hokudai.ac.jp
kbt@eng.hokudai.ac.jp
hajito@eng.hokudai.ac.jp
[b] Division of Applied Chemistry, Graduate School of Engineering, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan

Published as part of the
Special Issue Honoring Masahiro Murakami's Contributions to Science



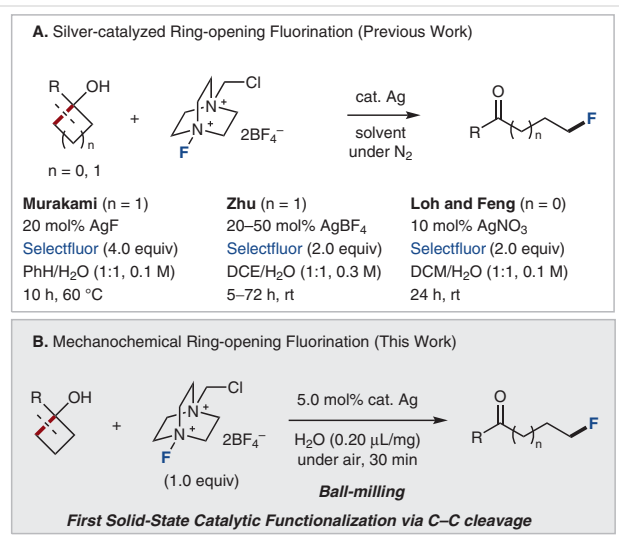
Received: 18.11.2022
Accepted after revision: 29.01.2023
Published online: 29.01.2023 (Accepted Manuscript), 03.05.2023 (Version of Record)
DOI: 10.1055/a-2021-9599; Art ID: ST-2022-11-0498-C

Abstract In this report, we demonstrate that a ball-milling technique facilitates fast and efficient silver-catalyzed ring-opening fluorination of cyclobutanols. This is the first report of a catalytic C–C bond-cleavage/functionalization reaction under solid-state mechanochemical conditions. The developed protocol affords a high yield of γ-fluorinated ketones within much shorter reaction times, and requires less silver catalyst and Selectfluor compared with the previous solution-based conditions. Notably, the process can be carried out in air. Because of the reduced use of chemicals and the simple time-saving experimental procedures, this technique is an efficient and environmentally friendly way to access γ-fluorinated ketones.

Key words C–C bond cleavage, fluorination, mechanochemistry, ball-milling, solid-state chemistry, silver catalysis

In recent years, solvent-free solid-state organic transformations using ball-milling, known as mechanochemical reactions, have been extensively studied as new tools for organic chemistry.[1,2] Compared with conventional solution-based reactions, the advantages of these mechanochemical conditions include the avoidance of potentially harmful organic solvents, shorter reaction times, simple experimental operations, and the possibility of different reactivities from those in solution.[3] Owing to these advantages, a number of organic transformations have been attempted under mechanochemical conditions. Although the benefits of mechanochemistry for solid-state reactions of compounds with reactive bonds, such as organic halides, have been well demonstrated, nonactivated bond cleavage through mechanochemical transformation remains unexplored. Catalytic C–C bond-cleavage/functionalization reactions have great synthetic utility in the preparation of complex valuable molecules and have been well demonstrated under solution-based conditions, but these types of reactions under mechanochemical conditions have not been studied.

Fluorine-containing hydrocarbon motifs are often found in pharmaceuticals, agrochemicals, and materials.[4,5] Therefore, efficient methods to construct C(sp^3)–F bonds have been extensively researched over recent decades.[6] Ring-opening fluorination of cyclic compounds has attracted attention as a valuable method for remote C(sp^3)–F bond formation.[7,8] In pioneering studies in 2015, the groups of Murakami,[8b] Zhu,[8c] and Loh and Feng[8d] independently reported silver-catalyzed ring-opening fluorinations of cyclic alcohols (Scheme 1A). Although these C–C bond cleavage/fluorination reactions can provide efficient ways to synthesize γ-fluorinated ketones, the solution-based conditions require high catalyst loadings (>10 mol%), long reac-



Scheme 1 Silver-catalyzed ring-opening fluorination of cyclic alcohols

© 2023. Thieme. All rights reserved.

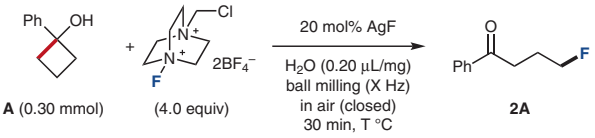
This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.

tion times, excessive amounts of Selectfluor, an inert-gas atmosphere, and toxic organic solvents. These requirements greatly reduce the practical utility of the ring-opening fluorination of cyclic alcohols. As part of our ongoing studies on mechanochemical synthesis, we proposed the transformation of this important reaction into a mechanochemical process.

Here, we report a silver-catalyzed ring-opening fluorination reaction of cyclic alcohols under solid-state mechanochemical conditions (Scheme 1B).[9] The reaction proceeded efficiently to produce the desired γ-fluorinated ketones with high yields in shorter reaction times and with smaller amounts of silver catalyst and Selectfluor than the established solution conditions. Notably, the entire newly developed solid-state protocol can be carried out under ambient conditions; i.e., the reactants, reagents, and catalysts can all be added to the milling jar in air. Thus, this operationally simple protocol provides a more convenient and sustainable alternative to conventional solution-based ring-opening fluorination. Importantly, this study is the first example of a catalytic C–C bond cleavage/functionalization reaction under mechanochemical conditions.

We began our study by exploring the milling conditions (milling jar, grinding ball, frequency, and internal temperature) of the solid-state ring-opening fluorination of 1-phenylcyclobutanol (**1A**) (Table 1). Reactions were conducted by using a Retsch MM400 mill equipped with a temperature-controllable heat gun [see the Supporting Information (SI) for details].[2f] Using the solution-based conditions discovered by the Murakami group[8b] for guidance, we carried the mechanochemical reaction of **1A** in the presence of 20 mol% AgF catalyst and 4.0 equivalents of Selectfluor, with H_2O (0.20 µL of liquid per mg of solid reactant) as a liquid assistant for the grinding process[10] in a stainless-steel jar (5 mL) with one 10 mm diameter stainless-steel grinding ball at 25 Hz for 30 min. The internal temperature was 110 °C, as determined by thermography (preset temperature: 200 °C). Under these conditions, the desired γ-fluorinated ketone **2A** was obtained in only 5% yield (Table 1, entry 1). Although a small amount of **2A** was generated, the mechanochemical reaction under these preliminary conditions resulted in a complex mixture and a poor mass balance. We hypothesized that the high-temperature mechanochemical conditions were too harsh due to the higher concentrations than those present in solution reactions. To make the reaction conditions milder, we next examined the reaction at a lower internal temperature. As expected, the yield of **2A** improved to 43% when the reaction was conducted at 55 °C (preset temperature: 80 °C) (entry 2). Lowering the frequency from 25 to 15 Hz gave a slightly better 46% yield of **2A** (entry 3). A shorter reaction time (10 min) at 30 Hz provided a poor result (10% yield; entry 4). These results suggest that the reaction temperature is the principal factor affecting the efficiency of this mechanochemical ring-opening fluorination reaction. In all cases, undesired decomposition of **1A** occurred during the reaction, and insoluble and unidentified compounds were found in the crude mixture. When the reaction was performed at room temperature, it was still incomplete after 30 min; a low yield of **2A** was obtained (7%), and 49% of **1A** was recovered (entry 5). Because decomposition of **1A** was still observed even under the milder conditions, we hypothesized that metallic residues from the stainless-steel milling jar or ball might interfere with the substrate, the silver catalyst, or Selectfluor, leading to undesired side reactions.[11,12] To confirm this, AgF was excluded from the mixture (Table 1, entry 6). Surprisingly, the ring-opening fluorination reaction still proceeded and gave **2A** in 28% yield, with 30% conversion of **1A** into unidentified byproducts. This result suggested that the stainless-steel milling jar and ball caused the side reactions. Other types of jars and balls made of other materials were therefore examined. We found that a ZrO_2 jar (10 mL) and ball (10 mm) resulted in a cleaner reaction mixture and produced **2A** in 52% yield (entry 7). A jar and ball made of Teflon, which has a low density, permitted gentle mixing and gave **2A** in a good yield of 51% (entry 8). On using a tungsten carbide jar (10 mL) and ball (10 mm), the yield of **2A** decreased significantly to 16% (entry 9). Based on these results, the optimal milling conditions were a 10 mL ZrO_2 jar with a 10 mm ZrO_2 ball at 15 Hz at 55 °C (Table 1, entry 7).

Table 1 Optimization of the Milling Conditions[a]



Entry	Jar/ball material	Frequency (Hz)	Internal temp (°C)	Yield[b] (%)
1	stainless-steel	25	110	5
2	stainless-steel	25	55	43
3	stainless-steel	15	55	46
4[c]	stainless-steel	30	55	10
5	stainless-steel	15	35	7
6[d]	stainless-steel	15	55	28
7	ZrO_2	15	55	52
8	Teflon	15	55	51
9	tungsten carbide	15	55	16

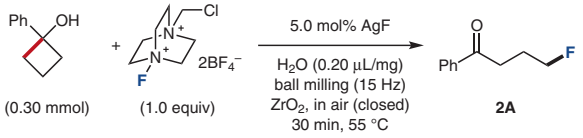
[a] Conditions: **1A** (0.30 mmol), AgF (20 mol%), Selectfluor (4.0 equiv), H_2O (0.20 µL/mg), milling jar, milling ball.
[b] Determined by ^{1}H NMR analysis with CH_2Br_2 as an internal standard.
[c] Reaction time 10 min.
[d] Reaction conducted without AgF.

Further optimization of the conditions was subsequently carried out using the ZrO_2 milling jar and ball (Table 2). After extensive experimentation, the standard conditions were defined as follows: AgF (5.0 mol%) and Selectfluor (1.0

This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.

equiv) with a small volume of H_2O (0.20 µL/mg) under the optimal milling conditions for 30 min. By using these conditions, **1A** was converted into **2A** in 68% yield (Table 2, entry 1). At a higher catalyst loading, **1A** was entirely consumed, but the yield of **2A** decreased (entry 2). This result suggested that a higher silver catalyst loading increases the concentration of reactive radical species and causes undesired side reactions. A lower catalyst loading (2.5 mol%) and a shorter reaction time (15 min) gave nearly identical results to the standard conditions (entry 3). Other metal additives, such as manganese or iron salts, known to be effective catalysts under solution conditions, were not suitable for this solid-state reaction (entries 4 and 5).[8d,h] When AgF was excluded from the standard conditions, the reaction did not proceed (entry 6).

Table 2 Catalyst Optimization Using a ZrO_2 Milling Jar and Ball[a]



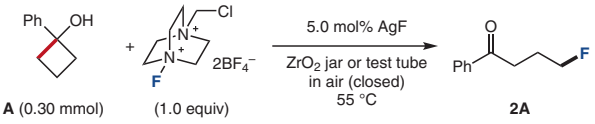
Entry	Deviation from the standard conditions	Yield[b] (%)
1	none	68
2	20 mol% AgF	55
3	2.5 mol% AgF, 15 min	70
4	20 mol% $Mn(OAc)_2{\cdot}4H_2O$	27
5	20 mol% $Fe(acac)_2$	–
6	no AgF	–

[a] Standard conditions: **1A** (0.30 mmol), AgF (5.0 mol%), Selectfluor (1.0 equiv), H_2O (0.20 µL/mg), 55 °C (internal temp), 30 min, ZrO_2 ball-milling jar (10 mL) with a ZrO_2 ball (10 mm), ball-milling at 15 Hz.
[b] Determined by ^{1}H NMR analysis with CH_2Br_2 as the internal standard.

Having determined the optimal conditions, we next examined the substrate scope (Scheme 2). A simple phenyl-substituted cyclobutanol **1A** reacted well and produced the corresponding fluoro ketone **2A** in 68% yield. Sterically hindered 1-mesitylcyclobutanol (**1B**) produced the ring-opened compound **2B** in 39% yield. Substrates with aromatic substituents bearing an electron-donating methoxy group readily underwent fluorination to give the γ-fluorinated acetophenones **2C** and **2D** in yields of 62 and 80%, respectively. The presence of phenoxy or trifluoromethyl substituents in the *para*-position in **2E** and **2F**, respectively, reduced the efficiency of the reaction. In these cases, even in the presence of 10 mol% AgF catalyst, the reaction required a longer time to produce the desired products in good yields (74 and 89%, respectively). Reactants with halo functionalities such as fluoro or chloro were suitable for use under these conditions (**2G** and **2H**). The reaction also proceeded with alkyl-substituted cyclobutanols, producing the corresponding products **2I** and **2J** in yields of 50 and 44%, respectively. In the case of the naphthyl-substituted alcohol **1K**, a ring-opening intramolecular cyclization reaction occurred instead of the fluorination reaction, giving ketone **3** in 41% yield.[13] When heteroaromatic compounds such as the pyridine derivative **1L** or the thiophene derivative **1M** were subjected to these reaction conditions, the starting materials decomposed into complex mixtures. Less-ring-strained 1-phenylcyclopentanol (**1N**) and 1-phenylcyclohexanol (**1O**) afforded the corresponding fluorinated ketones **2N** and **2O** in lower yields (10 and 12%, respectively), in contrast to the favorable results observed with these substrates under solution-based conditions.[8d] These low yields were primarily caused by an undesired dehydration or protonation reaction that gave the alkenes **4** and **6** and the simple ketone **5**. In addition, high concentrations of the starting materials remained after the reactions of **1N** and **1O**.[14]

To demonstrate the practical utility of the solid-state ball-milling reaction, solution and neat-stirring reactions were performed in screw-capped tubes under conditions similar to the mechanochemical standard conditions (Table 3). The solution reaction of **1A** was conducted in the presence of AgF (5.0 mol%) and Selectfluor (1.0 equiv) in a 1:1 water/benzene biphasic system (2.0 mL) at 55 °C under ambient atmosphere with magnetic stirring at 500 rpm. This solvent system was used by the Murakami group in their work.[8b] Under these conditions, **2A** was obtained in very low yields of 2% after 30 minutes and 6% after 12 hours. The neat-stirring reaction progressed with low efficiency to yield the desired fluorinated ketone **2A** in 27% yield, suggesting that the strong mechanical agitation induced by ball milling is crucial for successful solid-state fluorination.

Table 3 Comparative Studies under Solution-State and Neat Conditions

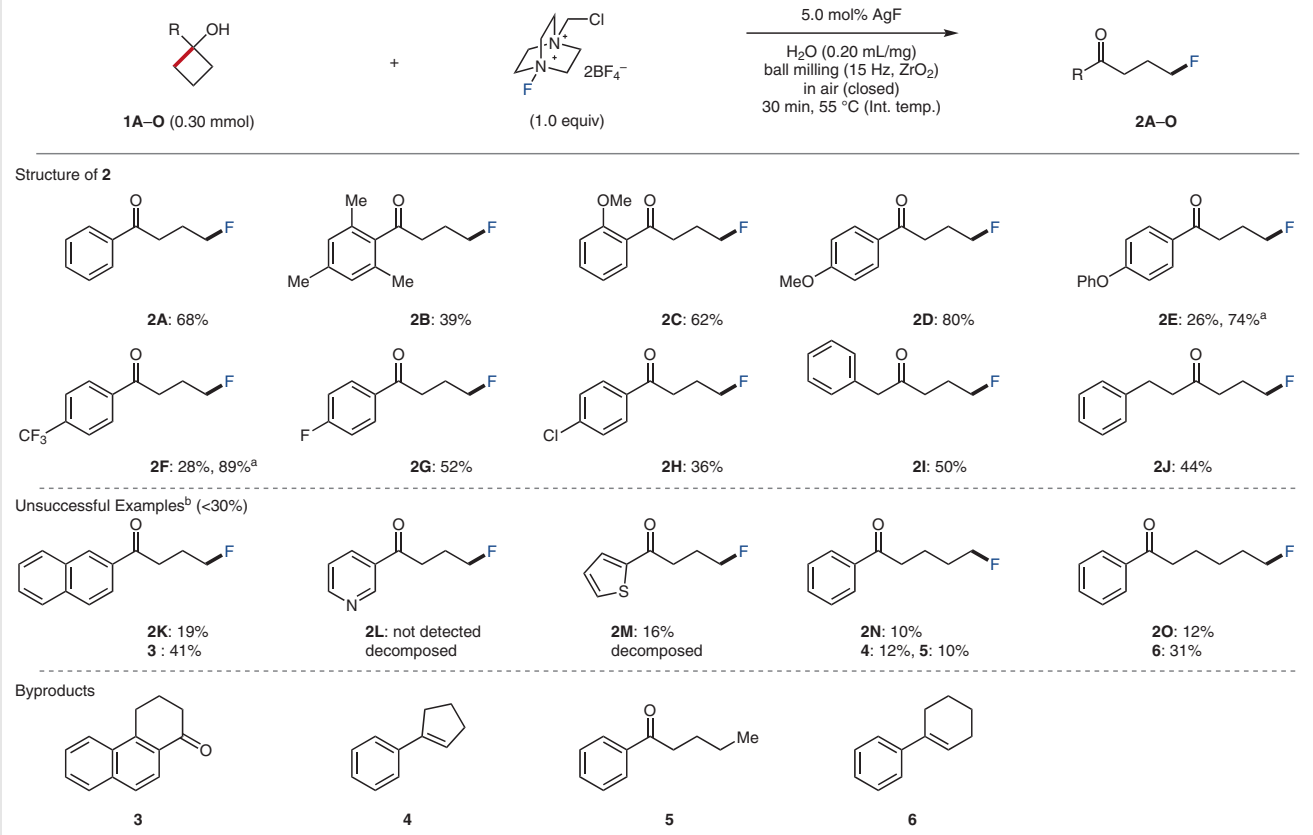


	Ball-milling (15 Hz)	Solution-state (500 rpm)	Neat (500 rpm)
Yield[a] (%)	68 (30 min)	2 (30 min) 6 (12 h)	27 (30 min)

[a] Determined by ^{1}H NMR analysis with CH_2Br_2 as the internal standard.

To investigate the reaction mechanisms in the solid state, we performed radical-trapping experiments (see the SI for details). We found that the addition of TEMPO as a radical scavenger completely inhibited the desired ring-opening fluorination. This result was consistent with the previously reported solution-state reactions. We therefore

This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.



Scheme 2 Substrate scope for the solid-state ring-opening fluorination. *Reaction conditions*: **1A** (0.30 mmol), 5.0 mol% AgF, Selectfluor (1.0 equiv), H_2O (0.20 mL/mg), 55 °C (internal temperature), 30 min, ZrO_2 ball-milling jar (10 mL) with a ZrO_2 ball (10 mm), ball-milling (15 Hz). [a] 10 mol% AgF for 1 h. [b] Yields determined by ^{1}H NMR analysis with CH_2Br_2 as the internal standard.

assume that this solid-state reaction has a radical-type reaction mechanism, similar to that under solution-state conditions.

In summary, we have developed a method for a silver-catalyzed solid-state ring-opening fluorination of cyclobutanols under ball-milling conditions.[15] This is the first example of a catalytic C–C bond cleavage/functionalization reaction under solid-state mechanochemical conditions. The developed mechanochemical conditions do not require potentially harmful organic solvents, and they use less silver catalyst and Selectfluor than previously reported solution-state conditions. Notably, all synthetic operations can be carried out in air. Considering these practical utilities, the present solid-state ring-opening fluorination is an efficient and environmentally friendly strategy for accessing γ-fluorinated ketones. Further studies to expand the scope of cyclic alcohols and the development of unique C–C bond-cleavage reactions in the solid state are ongoing in our laboratory.

Conflict of Interest

The authors declare no conflict of interest.

Funding Information

This work was financially supported by the Japan Society for the Promotion of Science (JSPS) via KAKENHI grants 22H00318, 21H01926, 22K18333, 22H05328, and 22K20523, by the JST via the CREST grant JPMJCR19R1, by the FOREST grant PJ2521A02I, and by the Institute for Chemical Reaction Design and Discovery (ICReDD), established by the World Premier International Research Initiative (WPI), MEXT, Japan.

Acknowledgment

We thank Mr. Yuma Shiratori for his help in crosschecking the experiments.

Supporting Information

Supporting information for this article is available online at https://doi.org/10.1055/a-2021-9599.

This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.

References and Notes

(1) For selected reviews on the use of ball-milling for organic synthesis, see: (a) James, S. L.; Adams, C. J.; Bolm, C.; Braga, D.; Collier, P.; Friščić, T.; Grepioni, F.; Harris, K. D. M.; Hyett, G.; Jones, W.; Krebs, A.; Mack, J.; Maini, L.; Orpen, A. G.; Parkin, I. P.; Shearouse, W. C.; Steed, J. W.; Waddell, D. C. *Chem. Soc. Rev.* **2012**, *41*, 413. (b) Wang, G.-W. *Chem. Soc. Rev.* **2013**, *42*, 7668. (c) Do, J.-L.; Friščić, T. *ACS Cent. Sci.* **2017**, *3*, 13. (d) Hernández, J. G.; Bolm, C. *J. Org. Chem.* **2017**, *82*, 4007. (e) Métro, T.-X.; Martinez, J.; Lamaty, F. *ACS Sustainable Chem. Eng.* **2017**, *5*, 9599. (f) Achar, T. K.; Bose, A.; Mal, P. *Beilstein J. Org. Chem.* **2017**, *13*, 1907. (g) Eguaogie, O.; Vyle, J. S.; Conlon, P. F.; Gîlea, M. A.; Liang, Y. *Beilstein J. Org. Chem.* **2018**, *14*, 955. (h) Howard, J. L.; Cao, Q.; Browne, D. L. *Chem. Sci.* **2018**, *9*, 3080. (i) Andersen, J.; Mack, J. *Green Chem.* **2018**, *20*, 1435. (j) Bolm, C.; Hernández, J. G. *Angew. Chem. Int. Ed.* **2019**, *58*, 3285. (k) Friščić, T.; Mottillo, C.; Titi, H. M. *Angew. Chem. Int. Ed.* **2020**, *59*, 1018. (l) Kubota, K.; Ito, H. *Trends Chem.* **2020**, *2*, 1066. (m) Porcheddu, A.; Colacino, E.; De Luca, L.; Delogu, F. *ACS Catal.* **2020**, *10*, 8344. (n) Virieux, D.; Delogu, F.; Porcheddu, A.; García, F.; Colacino, E. *J. Org. Chem.* **2021**, *86*, 13885. (o) Cuccu, F.; De Luca, L.; Delogu, F.; Colacino, E.; Solin, N.; Mocci, R.; Porcheddu, A. *ChemSusChem* **2022**, *15*, e202200362. (p) Shaw, T. E.; Mathivathanan, L.; Jurca, T. *Organometallics* **2019**, *38*, 4066. (q) Hwang, S.; Grätz, S.; Borchardt, L. *Chem. Commun.* **2022**, *58*, 1661.

(2) For selected examples of solid-state organic transformations using ball-milling from our group, see: (a) Kubota, K.; Pang, Y.; Miura, A.; Ito, H. *Science* **2019**, *366*, 1500. (b) Kubota, K.; Takahashi, R.; Ito, H. *Chem. Sci.* **2019**, *10*, 5837. (c) Kubota, K.; Seo, T.; Koide, K.; Hasegawa, S.; Ito, H. *Nat. Commun.* **2019**, *10*, 111. (d) Pang, Y.; Lee, J. W.; Kubota, K.; Ito, H. *Angew. Chem. Int. Ed.* **2020**, *59*, 22570. (e) Seo, T.; Kubota, K.; Ito, H. *J. Am. Chem. Soc.* **2020**, *142*, 9884. (f) Seo, T.; Toyoshima, T.; Kubota, K.; Ito, H. *J. Am. Chem. Soc.* **2021**, *143*, 6165. (g) Kubota, K.; Toyoshima, N.; Miura, D.; Jiang, J.; Maeda, S.; Jin, M.; Ito, H. *Angew. Chem. Int. Ed.* **2021**, *60*, 16003. (h) Takahashi, R.; Hu, A.; Gao, P.; Gao, Y.; Pang, Y.; Seo, T.; Maeda, S.; Jiang, J.; Takaya, H.; Kubota, K.; Ito, H. *Nat. Commun.* **2021**, *12*, 6691. (i) Kubota, K.; Kondo, K.; Seo, T.; Ito, H. *Synlett* **2022**, *33*, 898.

(3) (a) Colacino, E.; Isoni, V.; Crawford, D.; García, F. *Trends Chem.* **2021**, *3*, 335. (b) Ardila-Fierro, K. J.; Hernández, J. D. *ChemSusChem* **2021**, *14*, 2145. (c) Fantozzi, N.; Volle, J.-N.; Porcheddu, A.; Virieux, D.; García, F.; Colacino, E. *ChemRxiv* **2022**, preprint DOI: 10.26434/chemrxiv-2022-b370p.

(4) (a) Müller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *317*, 1881. (b) Hagmann, W. K. *J. Med. Chem.* **2008**, *51*, 4359. (c) Purser, S.; Moore, P. R.; Swallow, S.; Gouverneur, V. *Chem. Soc. Rev.* **2008**, *37*, 320. (d) Beger, R.; Resnati, G.; Metrangolo, P.; Weber, E.; Hulliger, J. *Chem. Soc. Rev.* **2011**, *40*, 3496. (e) Cametti, M.; Crousse, B.; Metrangolo, P.; Milani, R.; Resnati, G. *Chem. Soc. Rev.* **2012**, *41*, 31. (f) Jacobson, O.; Kiesewetter, D. O.; Chen, X. *Bioconjugate Chem.* **2015**, *26*, 1. (g) Gills, E. P.; Eastman, K. J.; Hill, M. D.; Donnelly, D. J.; Meanwell, N. A. *J. Med. Chem.* **2015**, *58*, 8315. (h) Yerien, D. E.; Bonesi, S.; Postigo, A. *Org. Biomol. Chem.* **2016**, *14*, 8398. (i) Meanwell, N. A. *J. Med. Chem.* **2018**, *61*, 5822. (j) Ogawa, Y.; Tokunaga, E.; Kobayashi, O.; Hirai, K.; Shibata, N. *iScience* **2020**, *23*, 101467. (k) Inoue, M.; Sumii, Y.; Shibata, N. *ACS Omega* **2020**, *5*, 10633.

(5) (a) Smart, B. E. *J. Fluorine Chem.* **2001**, *109*, 3. (b) O'Hagan, D. *Chem. Soc. Rev.* **2008**, *37*, 308. (c) Han, J.; Kiss, L.; Haibo, M.; Remete, A. M.; Ponikvar-Svet, M.; Sedgwick, D. M.; Roman, R.; Fustero, S.; Moriwaki, H.; Soloshonok, V. A. *Chem. Rev.* **2021**, *121*, 4678.

(6) For selected reviews, see: (a) Lian, T.; Constanze, N. N.; Ritter, T. *Angew. Chem. Int. Ed.* **2013**, *52*, 8214. (b) Brooks, A. F.; Topczewski, J. J.; Ichiishi, N.; Sanford, M. S.; Scott, P. J. H. *Chem. Sci.* **2014**, *5*, 4545. (c) Champagne, P. A.; Desroches, J.; Hamel, J.-D.; Vandamme, M.; Paquin, J.-F. *Chem. Rev.* **2015**, *115*, 9073. (d) Zhu, Y.; Han, J.; Wang, J.; Shibata, N.; Sodeoka, M.; Soloshonok, V. A.; Coelho, J. A. S.; Toste, F. D. *Chem. Rev.* **2018**, *118*, 3887. (e) Szpera, R.; Moseley, D. F. J.; Smith, L. B.; Sterling, A. J.; Gouverneur, V. *Angew. Chem. Int. Ed.* **2019**, *58*, 14824. (f) Bertrand, X.; Chabaud, L.; Paquin, J.-F. *Chem. Asian J.* **2021**, *16*, 563. (g) Suto, A.; Yamaguchi, J. *J. Synth. Org. Chem. Jpn.* **2021**, *79*, 910.

(7) For selected reviews of the ring-opening functionalization of cyclic alcohols, see: (a) Nikolaev, A.; Orellana, A. *Synthesis* **2016**, *48*, 1741. (b) Murakami, M.; Ishida, N. *Chem. Lett.* **2017**, *46*, 1692. (c) Liu, Y.; Wang, Q.-L.; Chen, Z.; Zhou, C.-S.; Xiong, B.-Q.; Zhang, P.-L.; Yang, C.-A.; Zhou, Q. *Beilstein J. Org. Chem.* **2019**, *15*, 256. (d) Wu, X.; Zhu, C. *Chem. Commun.* **2019**, *55*, 9747. (e) Tsui, E.; Wang, H.; Knowles, R. R. *Chem. Sci.* **2020**, *11*, 11124. (f) Murakami, M.; Ishida, N. *Chem. Rev.* **2021**, *121*, 264. (g) McDonald, T. R.; Mills, L. R.; West, M. S.; Rousseaux, S. A. L. *Chem. Rev.* **2021**, *121*, 3.

(8) For a review of ring-opening fluorination, see: (a) Remete, A. M.; Kiss, L. *Eur. J. Org. Chem.* **2019**, 5574. For selected examples of the ring-opening fluorination, see: (b) Ishida, N.; Okuma, S.; Nakanishi, Y.; Murakami, M. *Chem. Lett.* **2015**, *44*, 821. (c) Zhao, H.; Fan, X.; Yu, J.; Zhu, C. *J. Am. Chem. Soc.* **2015**, *137*, 3490. (d) Ren, S.; Feng, C.; Loh, T.-P. *Org. Biomol. Chem.* **2015**, *13*, 5105. (e) Bloom, S.; Bume, D. D.; Pitts, C. R.; Lectka, T. *Chem. Eur. J.* **2015**, *21*, 8060. (f) Deng, Y.; Kauser, N. I.; Islam, S. M.; Mohr, J. T. *Eur. J. Org. Chem.* **2017**, 5872. (g) Lu, Y.-C.; Jordan, H. M.; West, J. G. *Chem. Commun.* **2021**, *57*, 1871. (h) Lu, Y.-C.; West, J. G. *ACS Catal.* **2021**, *11*, 12721. (i) Wu, P.; Ma, S. *Org. Lett.* **2021**, *23*, 2533. (j) Pitts, C. R.; Ling, B.; Snyder, J. A.; Bragg, A. E.; Lectka, T. *J. Am. Chem. Soc.* **2016**, *138*, 6598. (k) Banik, S. M.; Mennie, K. M.; Jacobsen, E. N. *J. Am. Chem. Soc.* **2017**, *139*, 9152. (l) Ilchenko, N. O.; Hedberg, M.; Szabó, K. J. *Chem. Sci.* **2017**, *8*, 1056. (m) Wang, M.-M.; Waser, J. *Angew. Chem. Int. Ed.* **2020**, *59*, 16420. (n) Pitts, C. R.; Bloom, M. S.; Bume, D. D.; Zhang, Q. A.; Lectka, T. *Chem. Sci.* **2015**, *6*, 5225. (o) Dauncey, E. M.; Morcillo, S. P.; Douglas, J. J.; Sheikh, N. S.; Leonori, D. *Angew. Chem. Int. Ed.* **2018**, *57*, 744. (p) Kim, D.; Lim, H. N. *Org. Lett.* **2020**, *22*, 7465. (q) Song, J. W.; Lim, H. N. *Org. Lett.* **2021**, *23*, 5394. (r) Roque, J. B.; Kuroda, Y.; Göttemann, L. T.; Sarapong, R. *Science* **2018**, *361*, 171. (s) Komatsuda, M.; Suto, A.; Kondo, H. Jr.; Hiroyuki, T.; Kato, K.; Saito, B.; Yamaguchi, J. *Chem. Sci.* **2022**, *13*, 665. (t) Komatsuda, M.; Ohki, H.; Kondo, H. Jr.; Suto, A.; Yamaguchi, J. *Org. Lett.* **2022**, *24*, 3270.

(9) For selected examples of solid-state C(sp^3)–F bond construction, see: (a) Wang, Y.; Wang, H.; Jiang, Y.; Zhang, C.; Shao, J.; Xu, D. *Green Chem.* **2017**, *19*, 1674. (b) Howard, J. L.; Sagatov, Y.; Repusseau, L.; Schotten, C.; Browne, D. L. *Green Chem.* **2017**, *19*, 2798. (c) Howard, J. L.; Sagatov, Y.; Browne, D. L. *Tetrahedron* **2018**, *74*, 3118.

(10) (a) Bowmaker, G. A. *Chem. Commun.* **2013**, *49*, 334. (b) Ying, P.; Yu, J.; Su, W. *Adv. Synth. Catal.* **2021**, *363*, 1246.

(11) Štefanić, G.; Krehula, S.; Štefanić, I. *Chem. Commun.* **2013**, *49*, 9245.

This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.

(12) For selected examples of reactions in which a milling ball or jar works as a metal catalyst, see: (a) Hwang, S.; Grätz, S.; Borchardt, L. *Chem. Commun.* **2022**, *58*, 1661. (b) Fulmer, D. A.; Shearouse, W. C.; Medonza, S. T.; Mack, J. *Green Chem.* **2009**, *11*, 1821. (c) Cook, T. L.; Walker, J. A. Jr.; Mack, J. *Green Chem.* **2013**, *15*, 617. (d) Yu, J.; Li, Z.; Jia, K.; Jiang, Z.; Liu, M.; Su, W. *Tetrahedron Lett.* **2013**, *54*, 2006. (e) Sawama, Y.; Niikawa, M.; Yabe, Y.; Goto, R.; Kawajiri, T.; Marumoto, T.; Takahashi, T.; Itoh, M.; Kimura, Y.; Sasai, Y.; Yamauchi, Y.; Kondo, S.; Kuzuya, M.; Monguchi, Y.; Sajiki, H. *ACS Sustainable Chem. Eng.* **2015**, *3*, 683. (f) Sawama, Y.; Kawajiri, T.; Niikawa, M.; Goto, R.; Yabe, Y.; Takahashi, T.; Marumoto, T.; Itoh, M.; Kimura, Y.; Monguchi, Y.; Kondo, S.; Sajiki, H. *ChemSusChem* **2015**, *8*, 3773. (g) Haley, R. A.; Zellner, A. R.; Krause, J. A.; Guan, H.; Mack, J. *ACS Sustainable Chem. Eng.* **2016**, *4*, 2464. (h) Sawama, Y.; Yasukawa, N.; Bau, K.; Goto, R.; Niikawa, M.; Monoguchi, Y.; Itoh, M.; Sajiki, H. *Org. Lett.* **2018**, *20*, 2892. (i) Vogt, C. G.; Grätz, S.; Lukin, S.; Halasz, I.; Etter, M.; Evans, J. D.; Borchardt, L. *Angew. Chem. Int. Ed.* **2019**, *58*, 18942. (j) Pickhardt, W.; Beaković, C.; Mayer, M.; Wohlgemuth, M.; Kraus, F. J. L.; Etter, M.; Grätz, S.; Borchardt, L. *Angew. Chem. Int. Ed.* **2022**, e202205003.

(13) For silver-catalyzed ring expansion of cyclic alcohols, see: Yu, J.; Zhao, H.; Liang, S.; Bao, X.; Zhu, C. *Org. Biomol. Chem.* **2015**, *13*, 7924.

(14) For dehydration reaction of tertiary cyclic alcohols using a copper catalyst and Selectfluor, see: Ren, S.; Zhang, J.; Zhang, J.; Wang, H.; Zhang, W.; Liu, Y.; Liu, M. *Eur. J. Org. Chem.* **2015**, 5381.

(15) **4-Fluoro-1-phenylbutan-1-one (2a); Typical Procedure**
Cyclobutanol **1A** (44.3 mg, 0.30 mmol, 1.0 equiv), AgF (1.9 mg, 0.015 mmol, 5.0 mol%), and Selectfluor (107.2 mg, 0.30 mmol, 1.0 equiv) were placed in a ball-milling vessel (ZrO_2, 10 mL) loaded with one grinding ball (ZrO_2; diameter: 10 mm). H_2O (31 µL, 0.20 µL/mg) was added from a syringe. The vessel was then closed in air without purging with an inert gas, and placed in the ball mill (Retsch MM400) for 30 min at 15 Hz with heating by a heat gun to an internal temperature of 55 °C. After 30 min, H_2O and Et_2O were added and the mixture was extracted with Et_2O (×3). The combined organic layer was dried ($MgSO_4$), filtered, and concentrated in vacuo. The crude product was purified by flash column chromatography [silica gel, hexane–EtOAc, 50:1] to give a colorless oil; yield: 33.8 mg (68%).
^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.16 (d quint, *J* = 27.6, 6.4 Hz, 2 H), 3.16 (t, *J* = 6.4 Hz, 2 H), 4.57 (dt, *J* = 48.8, 6.4 Hz, 2 H), 7.48 (t, *J* = 8.0 Hz, 2 H), 7.58 (t, *J* = 8.0 Hz, 1 H), 7.99 (d, *J* = 8.0 Hz, 2 H). ^{13}C NMR (101 MHz $CDCl_3$): δ = 24.8 (d, $J_{C–F}$ = 20.2 Hz, CH_2), 33.9 (d, $J_{C–F}$ = 4.8 Hz, CH_2), 83.3 (d, $J_{C–F}$ = 165.9 Hz, CH_2), 127.9 (*C*H), 128.6 (*C*H), 133.1 (*C*H), 136.7 (*C*), 199.0 (*C*). ^{19}F NMR (376 MHz $CDCl_3$): δ = –220.9 to –221.4 (m, 1 F). HRMS-EI: *m/z* $[M]^+$ calcd for $C_{10}H_{11}FO$: 166.07939; found: 166.07934. The NMR spectra agreed with those reported in the literature.[8h]

This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.